

Contract Report SL-96-2
UAST-CR-93-004

JOINT U.S./ROK R&D PROGRAM FOR NEW UNDERGROUND AMMUNITION STORAGE TECHNOLOGIES

FINAL REPORT IMPROVED TECHNIQUES FOR MEASURING THERMAL EFFECTS OF PROPELLANT BURN TESTS IN CONFINED AREAS

by

E. C. Knox

DTIC QUALITY INSPECTED

REMTECH, Inc.
2905 West Corp Boulevard,
Suite 112
Huntsville, Alabama 35805

May 1996

Prepared for U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, Mississippi 39180-6199

19960619 064

DISTRIBUTION STATEMENT

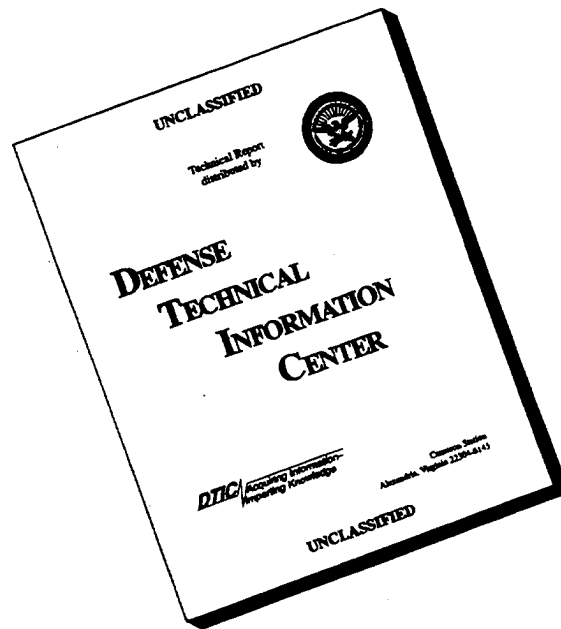
Approved for public release;
Distribution Unlimited

The contents of this report are not to be used for advertising, publication, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.



PRINTED ON RECYCLED PAPER

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.



**US Army Corps
of Engineers**
Waterways Experiment
Station

Contract Report SL-96-2
May 1996

Joint U.S./ROK R&D Program for New Underground Ammunition Storage Technologies

Improved Techniques for Measuring Thermal Effects of Propellant Burn Tests in Confined Areas

by *E. C. Knox*
REMTECH, Inc.

WES

Approved For Public Release; Distribution Is Unlimited.

Improved Techniques for Measuring Thermal Effects of Propellant Burn Tests in Confined Areas

by **E. C. Knox**

**REMTECH, Inc.
2905 West Corp Boulevard, Suite 112
Huntsville, AL 35805**

Final report

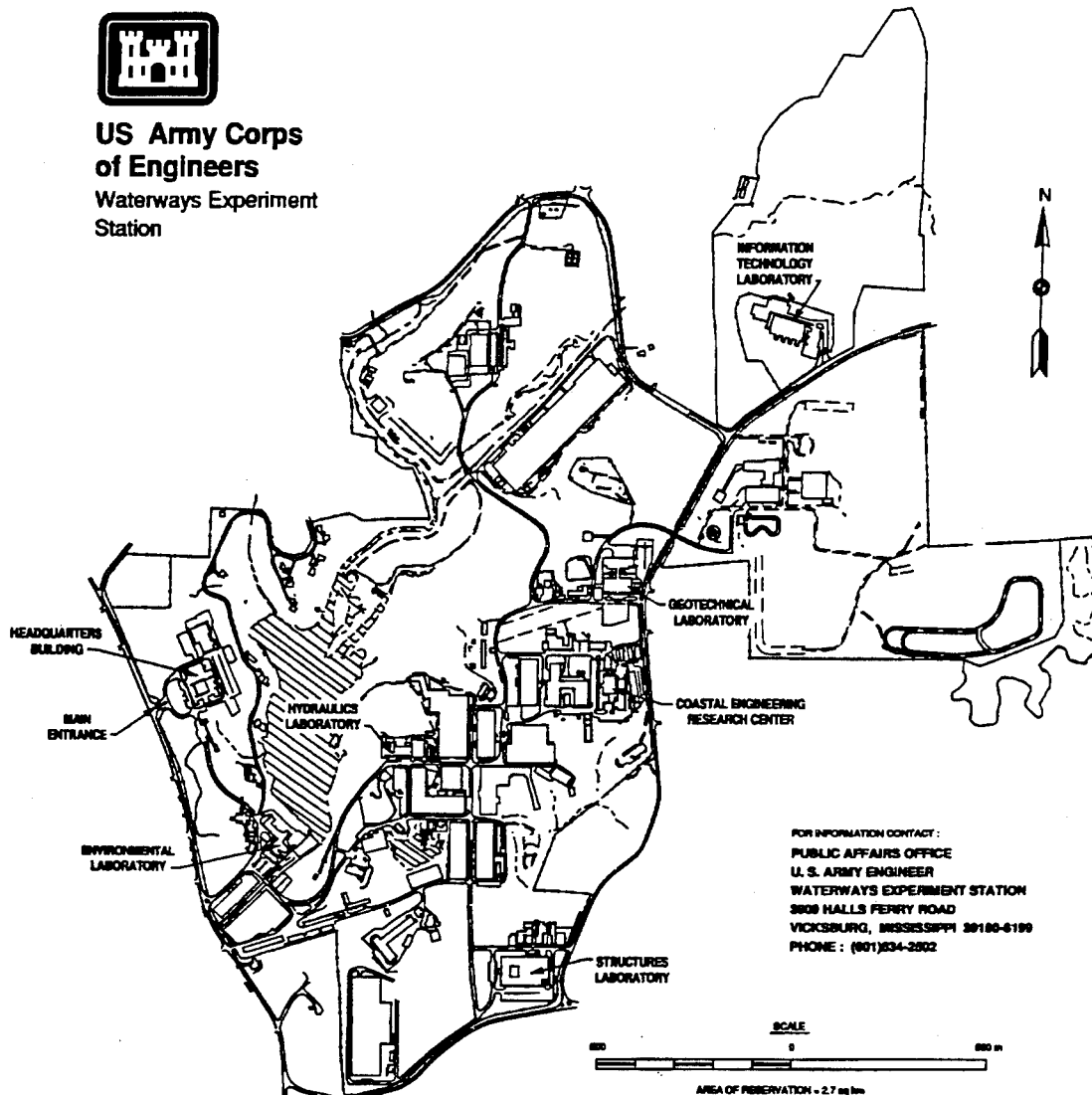
Approved for public release; distribution is unlimited

**Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000**

**Monitored by U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199**



**US Army Corps
of Engineers**
Waterways Experiment
Station



Waterways Experiment Station Cataloging-in-Publication Data

Knox, E. C.

Improved techniques for measuring thermal effects of propellant burn tests in confined areas / by E.C. Knox ; prepared for U.S. Army Corps of Engineers ; monitored by U.S. Army Engineer Waterways Experiment Station.

54 p. : ill. ; 28 cm. — (Contract report ; SL-96-2)

"UAST-CR-93-004"—T.p.

Includes bibliographical references.

1. Ammunition — Storage. 2. Propellant actuated devices. 3. Propellants — Thermal properties. 4. Underground storage. I. United States. Army. Corps of Engineers. II. U.S. Army Engineer Waterways Experiment Station. III. Structures Laboratory (U.S. Army Engineer Waterways Experiment Station) IV. Joint U.S./ROK R&D Program for New Underground Ammunition Storage Technologies. V. Title. VI. Series: Contract report (U.S. Army Engineer Waterways Experiment Station) ; SL-96-2.

TA7 W34c no.SL-96-2

Contents

List of Figures	iv
List of Tables	iv
Preface	v
Nomenclature	vi
Conversion Factors	vii
1 INTRODUCTION	1
2 OBJECTIVES	2
3 PROPELLANT THERMOCHEMICAL PROPERTIES	3
3.1 Propellant Thermochemical Properties	3
3.2 Propellant Burning Properties	4
4 ANALYTICAL FLOW MODEL	7
4.1 Flow Model Development	7
4.2 Flow Model Application	7
5 TEST RESULTS REVIEW AND COMPARISON WITH ANALYSIS	13
5.1 Plume, Bunker Pressure and Temperature Measurements Review	13
5.2 Vent Pipe Heat Flux Measurement Review	14
6 RECOMMENDED INSTRUMENTATION FOR FUTURE PROPELLANT BURN TESTS	18
6.1 Propellant Combustion Chamber Instrumentation	19
6.2 Vent Pipe Instrumentation	20
6.3 Plume Instrumentation	21
6.4 Recommended Data Reduction and Instrumentation Installation	22
7 REFERENCES	25
Appendix A ANALYSIS OF ADIABATIC BURNING CONDITION OF M-1 PROPELLANT USED IN KA-III, PHASE C, TESTS (CEC Code Output)	A-1
Appendix B ANALYSIS OF ISENTROPIC BURNING CONDITION OF M-1 PROPELLANT USED IN KA-III, PHASE C, TESTS (CEC Code Output)	B-1
Appendix C SPECIFICATION SHEETS FOR THE RECOMMENDED THERMAL INSTRUMENTATION	C-1

LIST OF FIGURES

1	M-1 Propellant Grain Geometry	5
2	Variation of Ejected Combustible Material with Vent Diameter (from Ref. [4])	6
3	KA-III, Phase C, Test C-3 Bunker Pressure Histories	10
4	KA-III, Phase C, Test C-3 Bunker Gas Temperature History	11
5	KA-III, Phase C, Test C-3 Post-peak Bunker Pressure Histories	12
6	KA-III, Phase C, Test C-3 Bunker Pressure and Gas Temperature Histories	15
7	Power-law Correlation of KA-III, Phase C, Test C-3 TF191 Heat Flux History to Bunker Pressure History	16
8	Power-law Correlation of KA-III, Phase C, Test C-3 TF192 Heat Flux History to Bunker Pressure History	17
9	Recommended Instrumentation in Combustion Chamber for WES May '93 Propellant Burn Tests	19
10	Recommended Instrumentation in Vent Pipe for WES May '93 Propellant Burn Tests	21
11	Recommended Instrumentation in Plume Region for WES May '93 Propellant Burn Tests	22
C-1	Recommended Chamber Total Temperature Instrumentation for WES May '93 Propellant Burn Tests	C-2
C-2	Recommended Total Heat Flux/Surface Thermocouple Instrumentation for WES May '93 Propellant Burn Tests	C-3
C-3	Recommended Radiometer Instrumentation for WES May '93 Propellant Burn Tests	C-4
C-4	Recommended Vent Pipe and Plume Total Temperature Instrumentation for WES May '93 Propellant Burn Tests	C-5

LIST OF TABLES

1	WES May '93 Propellant Burn Tests Recommended Instrumentation Summary	18
---	---	----

PREFACE

This study was conducted for the U.S. Army Engineer Waterways Experiment Station (WES) under contract DACA39-92-M-7281 as part of the Joint U.S./Republic of Korea (ROK) R&D Study for New Underground Ammunition Storage Technologies. Technical Managers for the Joint Program were Mr. Landon K. Davis, Geomechanics and Explosions Effects Division (GEED), WES, and Dr. So-young Song, Korean Agency for Defense Development. The Program Managers were Mr. Gary Abrisz, U.S. Army Technical Center for Explosives Safety, and COL Yeon Woo Chung, Logistics Bureau, Korean Ministry of Defense.

Mr. E. C. Knox, REMTECH, Inc., conducted the study reported herein and is the author of this report. The work was monitored by Mr. Charles E. Joachim, GEED, Structures Laboratory (SL), WES. Dr. Jimmy P. Balsara was Chief, GEED, and Mr. Bryant Mather was Director, SL.

At the time of preparation of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

The contents of this report are not to be used for advertising, publishing, or promotional purposes. Citation of trade names does not constitute an official endorsement or approval of the use of such commercial products.

NOMENCLATURE

A^*	Chocked flow area (= vent pipe area)
A_b	Propellant burning area
C_D	Orifice flow coefficient
P_c	Pressure in bunker
R	Propellant combustion gas constant, $C_p - C_v$
T_c	Measured gas temperature in bunker
V_c	Bunker volume, $\sim 5 \text{ m}^3$
r	Propellant surface burn, or recession rate, in./sec
t	Time for propellant ignition
γ	Ratio of gas specific heats, C_p/C_v
ρ	Density, gas or propellant

Subscripts

b	Denotes burning or propellant characteristic
c	Denotes chamber or bunker conditions/characteristics
p	Denotes peak value, as in peak pressure

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
atmospheres	101.325	kilopascals
BTU per square foot-second	1134.893	joule per square metre-second
calories per square inch-second	0.648521	joule per square centimetre-second
degrees	0.01745329	radians
degrees Fahrenheit	{5/9} {F-32}	Celsius
degrees Celsius	C + 273.15	Kelvins
degrees Kelvin	1.8	Ramkine
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	2.54	centimetres
kilowatts per square metre	1.000000	joule per square metre
litres	0.001	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pound (mass) per cubic inch	27.67990	grams per cubic centimetres
pounds (force) per square inch (psi)	6.894757	kilopascals

Section 1 INTRODUCTION

The U.S. Army Corps of Engineers, Waterways Experiment Station (WES), is conducting a test program to study the effects of the accidental burning of propellants stored in a confined area. This work is a part of a broader program called the Joint U.S./ROK (Republic of Korea) R&D Study for New Underground Ammunition Storage Technologies. The goal of the 5-year U.S./ROK Study is to develop improved designs for underground magazines which will greatly reduce the present external hazard areas that are required by current U.S. and Korean military safety standards to protect against the possibility of accidental fires and explosions.

Documentation of propellant burn tests performed to date is presented in Ref. [1]. Additional tests are planned; however, improvements to the instrumentation for these tests have been deemed necessary before executing them. REMTECH, Inc., was tasked by WES to review the instrumentation performance during the Ref. [1] tests and recommend improvements/additions to the Ref. [1] instrumentation for application to a subscale test scheduled for May 1993 at WES. Instrumentation performance experience during these tests will be factored into the instrumentation selection for full-scale tests to be conducted at a later time.

The results of this review are documented in the subject report.

Section 2

OBJECTIVES AND TECHNICAL APPROACH

The objectives for this review were to:

1. Develop improved instrumentation/techniques for measuring the thermal effects of propellant burn tests in confined areas.
2. Develop empirical methods for estimation of the thermal and fluid dynamic environments of the propellant burns.

The technical approach adopted to accomplish these objectives was divided into several phases: review of the available recorded data from Ref. [1] for each instrument channel in terms of quality and inter-channel compatibility; development of a preliminary one-dimensional model of the flow process; characterization of the propellant thermochemical properties; and comparison of results from the model and propellant characterization with the experimental results.

Section 3

PROPELLANT THERMOCHEMICAL PROPERTIES

As a means of establishing a standard by which the performance of the instrumentation for KA-III, Phase C, tests could be measured in terms of possible total energy release and likely pressure rise times, the thermochemical and burning properties of the propellant used in these tests were examined.

3.1 Propellant Thermochemical Properties

The propellant used in the KA-III, Phase C, tests and planned for use in the WES May '93 tests is, in the U.S. Army notation demoted as M-1. Its chemical composition is defined in Ref [2] and repeated herein as

Ingredient	Percent by weight
Ethanol (C_2H_6O)	0.75
Nitrocellulose ($C_6H_{7.3715}N_{2.6355}O_{10.2715}$)	83.74
Dinitrotoluene ($C_7H_6N_2O_4$)	9.84
Diphenylamine ($C_{12}NH_{11}$)	0.99
Butyl Phthalate ($C_{16}H_{22}O_4$)	4.93
Water (liquid)	0.50

This composition was input to REMTECH's in-house version of the NASA Chemical Equilibrium Composition code (CEC) [3] to determine the propellant combustion product and the amount of energy released upon burning.

Two burning condition were analyzed; adiabatic, representing the maximum possible energy release, and isentropic, representative of the propellant burning at one pressure and expanding isentropically to another pressure (atmospheric in this case). The resultant pressure and temperatures for these cases are tabulated as follows:

Condition	Pressure, atm	Temperature, K
Adiabatic	1810.	2437.
Isentropic	1.00	1919.

The complete CEC code outputs for these conditions are included in Appendices A and B, respectively. Therein the combustion products are listed to be approximately 50 percent CO, 20 percent H_2 , 13 percent water, 10 percent N_2 , and 6 percent CO_2 , with lesser amounts of other constituents.

Determination of the adiabatic properties was aided significantly by the assistance of Dr. A. J. Kotlar, USA Research Laboratory, Aberdeen Proving Ground, MD, which is hereby acknowledged.

3.2 Propellant Burning Properties

Mr. Michael M. Swisdak, Jr., Naval Surface Warfare Center/Dahlgren Division, is hereby acknowledged for his providing the geometry and burning characteristics for the M-1 propellant. Shown in Fig. 1 is the propellant geometry; its density is nominally 0.0566 lb/in.³, and its burn-rate equation is defined as

$$r = A * (Pressure)^N \quad (1)$$

where

r = the propellant burning surface recession rate (in./sec),

A = 0.00161 in./sec/psi, and

N = 0.741.

The time for a propellant grain to be consumed by burning for the conditions of the KA-III, Phase C, tests (Test C-3), using the log-mean pressure from initial to peak and the grain cylindrical surface area (inside and external) with the above equation, was estimated to be 0.40 sec.

Comparing this result with the actual burn time of approximately 10 seconds with the theoretical value of 0.40 seconds has several potential implications which include:

1. The entire surface areas of the pellets are not being ignited simultaneously.
2. The mass of the air in the bunker is significant compared with the burned propellant gas mass during the initial pressure buildup.
3. Stacking methods and container type probably influence the burn history since they may control the amount of surface area available for burning as a function of time.

As will be shown later in the report, the vent pipe exit velocity exceeds the combustion gas speed-of-sound (~2000 ft/sec) for portions of the burn history prior to and after the pressure peak. Considering the average grain burn time, any burning grains that become airborne during the burning process could travel as much as 800 ft while in the burning state, thus giving credence to the likelihood of burning propellant being ejected out of the bunker during the KA-III, Phase C, tests.

Similar effects were observed for tests reported in Ref [4], in which upwards to 80 percent of the combustible material was ejected out of the combustion chamber, depending on the vent diameter. Shown in Fig. 2 is a curve of the observed variation of the ejecta material percent vs. the vent diameter.

The presence of this phenomena in the instant process raises concerns as to the scalability of any subscale results to full-scale applications without an attendant math model of the flow process.

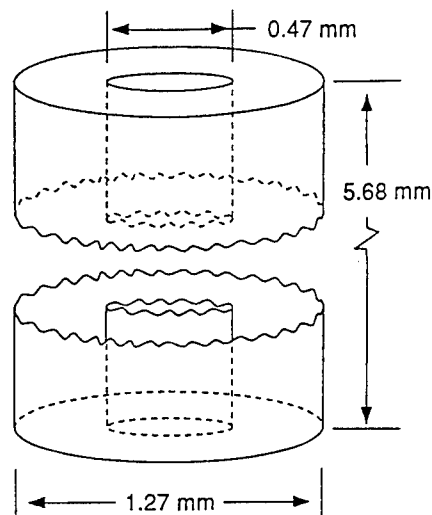


Figure 1. M-1 propellant grain geometry

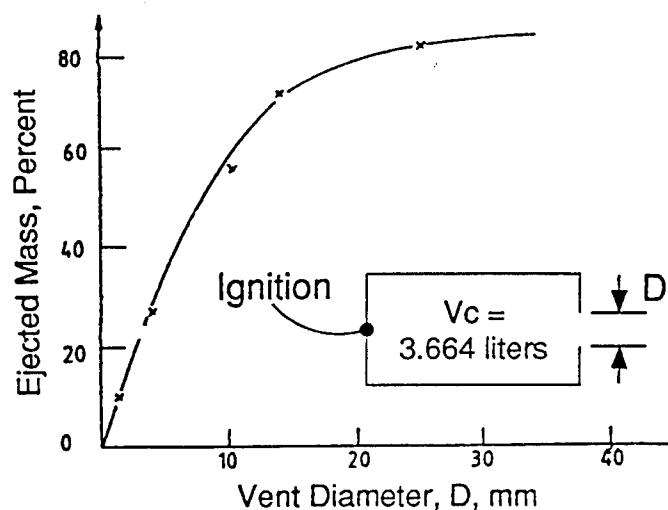


Figure 2. Variation of ejected combustible material with vent diameter, (Ref. [4])

Section 4

ANALYTICAL FLOW MODEL

As a means of establishing a standard by which the performance of the instrumentation for KA-III, Phase C, tests could be measured in terms of pressure histories and related heat transfer variations, a one-dimensional model of the flow process was developed.

4.1 Flow Model Development

Applying the conservation of mass principle to these tests, the combustion gas generated in the process of burning the propellant is accounted for in the accumulation of mass in the bunker and the mass that is vented out the connecting pipe. This balance is expressed in equation form as

$$A_b r \rho_b - \frac{d}{dt} (\rho_c V_c) = A P_c \sqrt{\frac{\gamma}{RT_c} \left(\frac{2}{\gamma - 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (2)$$

assuming the "choked" flow condition governs the vented mass flow rate, i.e., the condition for which the bunker pressure is greater than 1.9 times atmospheric pressure. Another expression applies for the "unchoked" condition.

4.2 Flow Model Application

Shown in Fig. 3 are the bunker pressure histories for test C-3 of the KA-III, Phase C Tests as measured by instruments ABI180, -181B, and 182. Also shown on Fig 3 is the division between "choked" and "unchoked" flow; at pressures greater than the division line, the "choked" form of Eq. (2) applies. The comparison temperature (TF190) history is presented in Fig. 4.

The exhibited pressure trends in Fig. 3 are interpreted as propellant burning until the pressure peak, after which pressure decay occurs as the bunker is vented to atmosphere. Then, for the pressure decay portion of the process, the mass generation term goes to zero in Eq. (2) preceding. The reduced Eq. (2) takes the form

$$\frac{dP_c}{dt} = - \frac{A}{V_c} \sqrt{RT_c \gamma \left(\frac{2}{\gamma - 1} \right)^{\frac{\gamma+1}{\gamma-1}}} P_c \quad (3)$$

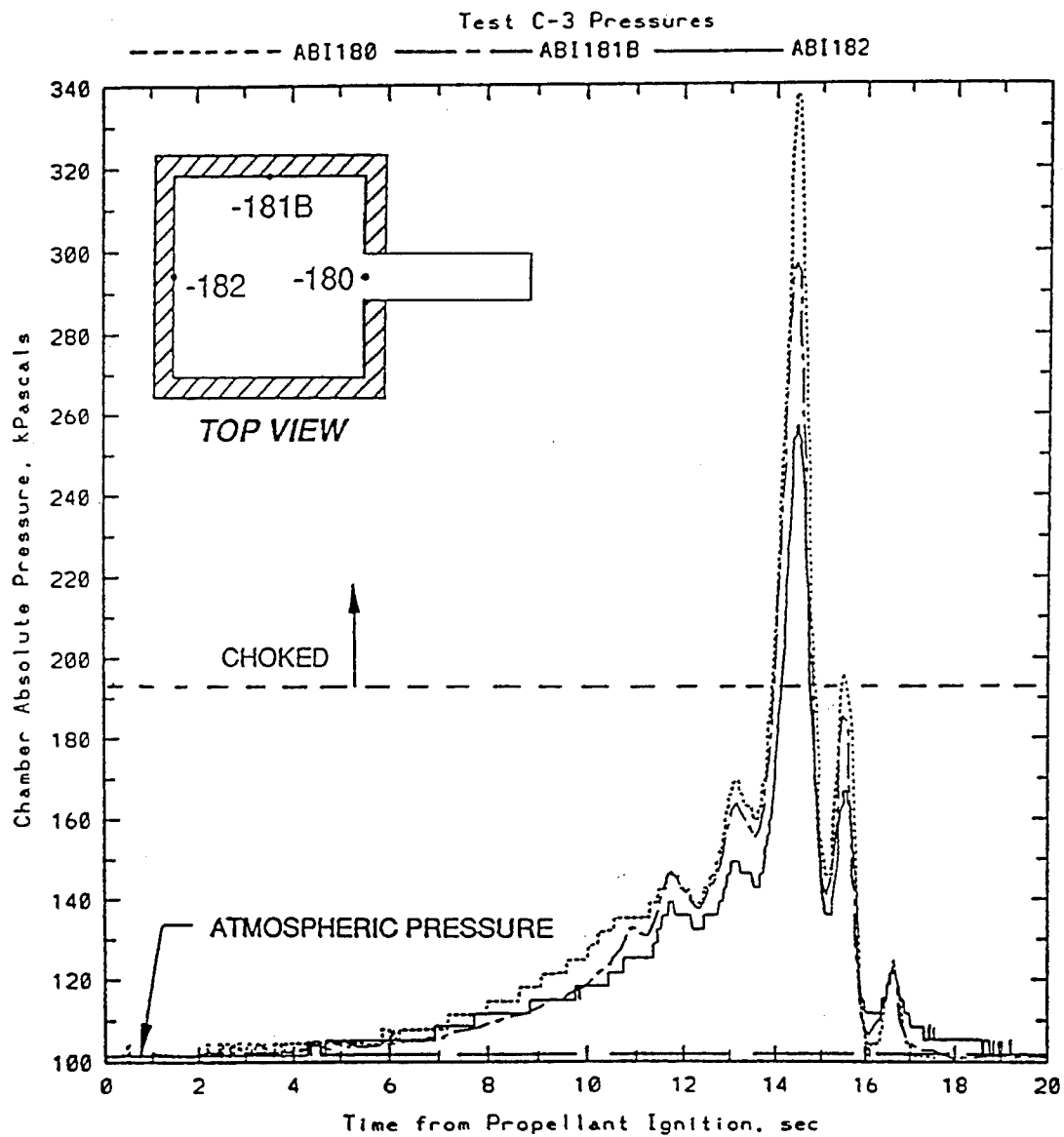


Figure 3. KA-III, Phase C, Test C-3 Bunker Pressure Histories.

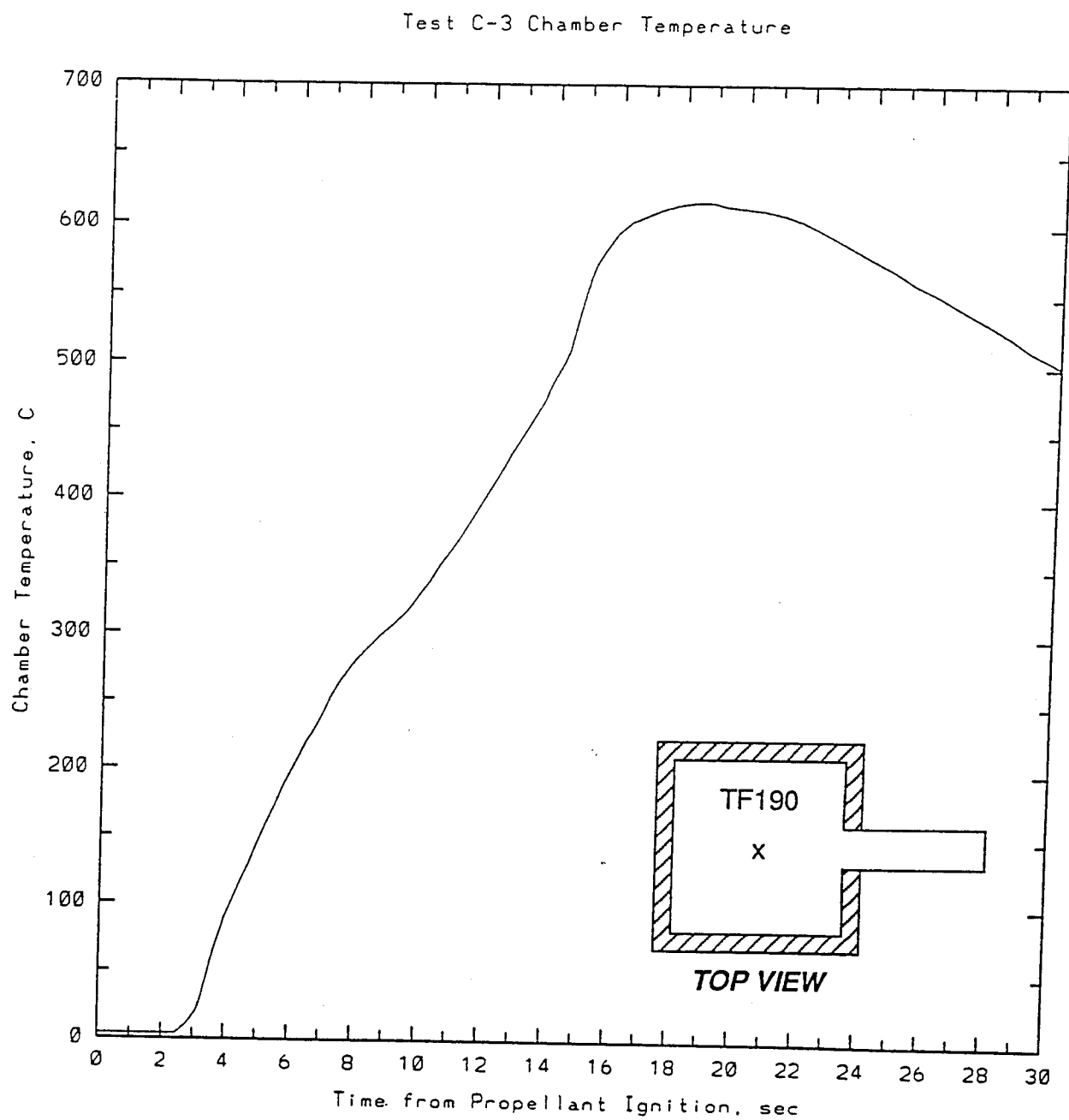


Figure 4. KA-III, Phase C, Test C-3 Bunker Gas Temperature History.

for which the solution takes the form

$$P_c(t) = (P_c)_p e^{-Bt}, \text{ where } B = \frac{A^*}{P_c} \sqrt{RT_c \gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (4)$$

The instant venting process may be related to venting through an orifice, so the constant, B , is redefined as $B * C_D$, where C_D is the discharge coefficient. C_D is a measure of the resistance offered by the orifice to passing the flow through it; a unity value denotes no resistance, i.e., isentropic flow, and values less than unity, increased resistance, typifying real flow with pressure losses and flow friction. The coefficient, B , was computed for the conditions of Test C-3 to be 5.666, treating the gas temperature as constant during the period of "choked" flow (≈ 14.0 to 15.0 sec). Hence, the particular solution for this case from Eq. (4) is

$$P_c(t) = (P_c)_p e^{-5.666 C_D t} \quad (5)$$

The pressure-decay portion of Fig. 3 is expanded in Fig. 5. Also presented in Fig. 5 are the computed pressure decay rates for $C_D = 1.0$ and 0.18 to illustrate the degree to which the measured decay is non-isentropic and the value of C_D required to match that decay. The normal range for the coefficient, C_D , to account for pressure losses in the orifice is 0.8 - 0.95; the value required to match the measured decay indicates significant other resistance mechanisms in operation. One such mechanism is thermal choking in the vent pipe, caused by heat release with time. This observation is in concert with the likelihood of burning propellant being ejected, and its definition would require the development of a particle transport mechanism model.

In Fig. 3 an apparent acoustical phenomena of the order of 1 Hz is manifested in the pressure history. Attempts to relate this occurrence to any of the geometric or flow parameters of this case have thus far proved unsuccessful, hence, its cause is not currently understood.

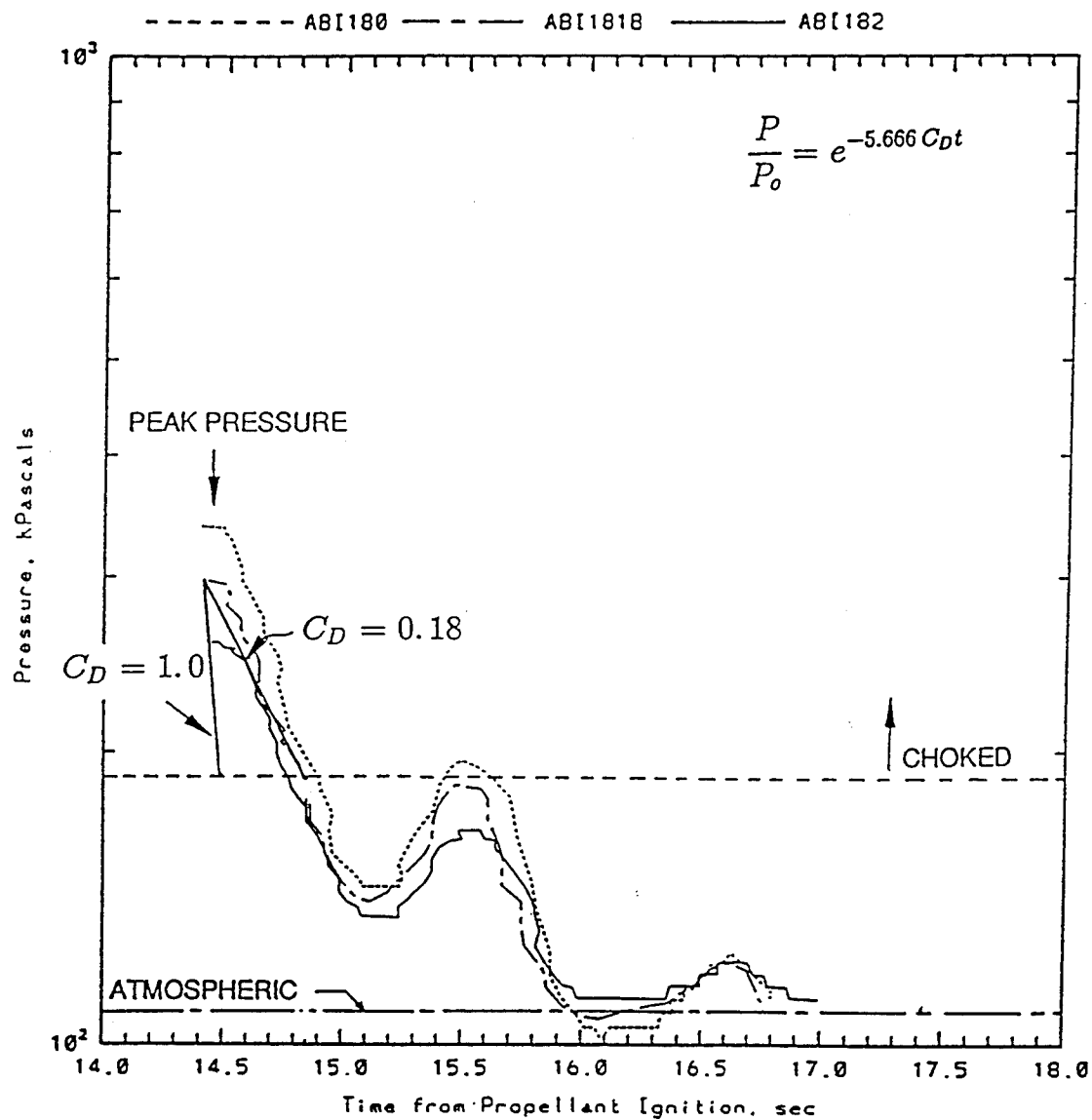


Figure 5. Ka-III, Phase C, Test C-3 Post-peak Bunker Pressure Histories

Section 5

TEST RESULT REVIEW AND COMPARISON WITH ANALYSIS

A review of the KA-III, Phase C Tests and comparison with analytical results based on the information and insights developed in the prior Sections are now presented to gauge the instrumentation performance. Two primary data sources were used: the Test Report [1], and the video footage of the plume history.

5.1 Plume, Bunker Pressure and Temperature Measurements Review

Review of the video coverage of the plume behavior during the propellant burns for all of the tests (C-1 through C-4) showed marked unsteadiness in the plume character, i.e., its shape, radiation intensity, and its apparent mean velocity. Moreover, on one occasion the plume was observed to be completely extinguished only to be subsequently re-ignited.

The observed unsteadiness likely is related to the acoustical phenomena detected in the pressure histories, so understanding this phenomena has more than a causal interest. The re-ignition process could be related to the presence of burning propellant grains or burning of the H_2 produced in the combustion products of the propellant burning process. To gain understanding of these plume characteristics, additional instrumentation to the surface pressures measured in the subject tests is necessary. Recommendations to define the required additional instrumentation are presented in the next Section.

Review of the plotted results presented in Ref [1] provide a better opportunity for direct comparisons and analysis with what one might expect based on fundamental thermochemical and fluid dynamic considerations. Of the four tests presented, the results for Test C-3 provided the better quality plots, hence our review focused on this test exclusively.

Possibly the most surprising aspect of our review was the apparent low amount of energy released in the bunker during the propellant burning compared to the amount theoretically available (See Section 3.1). The comparatively low pressure is possible in view of the vent and/or the slow burning time compared to the fluid dynamic time scale, i.e., the grains can be exhausted well into the plume before burning is completed. Moreover, the pressure histories from three transducers agree well enough to confirm the measurements as being correct.

However, the indicated gas temperature is well below the maximum value one might expect (900K compared to 1900K), suggesting either incomplete combustion in the burning process or very low rate producing little combustion gas. In the latter case the ambient air in the bunker affects measurably the mixture temperature. In addition, the shielded

thermocouples may have had significant time lag and conduction loss resulting in lower than actual indicated temperature.

In this vein the one bunker gas temperature measurement was compared chronologically with one of the bunker pressure histories as shown in Fig. 6. The temperature does not peak until about two seconds after the peak pressure occurs. Remembering the inference that the peak pressure indicates the cessation of propellant burning, the continued increase in gas temperature measurement suggests a thermal lag in the temperature measurement device. Future gas temperature instrumentation should be selected to minimize these potential effects.

5.2 Vent Pipe Heat Flux Measurements Review

A means of evaluating the performance of the heat flux instrumentation is the fundamental fluid dynamic relationship between the heat flux and local pressure. This relationship states that the heat flux is proportional to the pressure to an exponent, i.e.,

$$\dot{q} \propto (p)^n \quad (6)$$

where

$n = 0.85$ for turbulent flow.

Since the local pressure is related to the bunker pressure fluid dynamically and the bunker pressures were already digitized, one of the bunker pressure histories was used in the above equation with each of the two heat flux measurements (TF191 and -192). Shown in Figs. 7 and 8 are the heat flux histories for each measurement plotted against the bunker pressure in the log-log domain. Also shown is the 0.85 exponent line paired through the measurements. Good agreement with the fluid dynamic model is clearly evident, indicating the heat flux trends to be as expected and that the instrumentation is performing satisfactorily. It should be remembered, however, that instrumentation was severely overdriven in Test C-4, so for that reason a different type of instrument to measure heat flux is recommended in the following Section for the future tests.

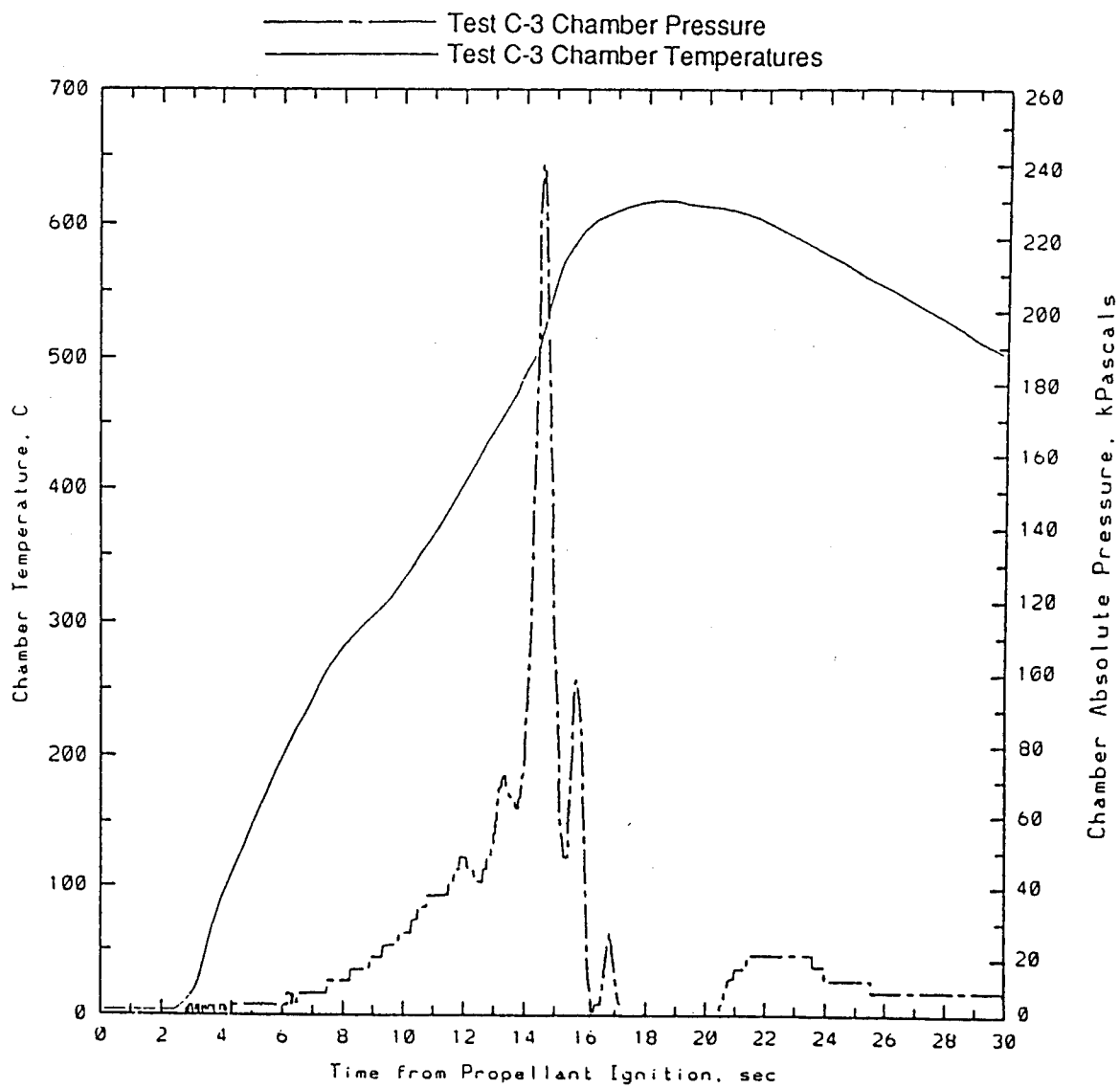


Figure 6. KA-III, Phase C, Test C-3 Bunker Pressure and Gas Temperature History.

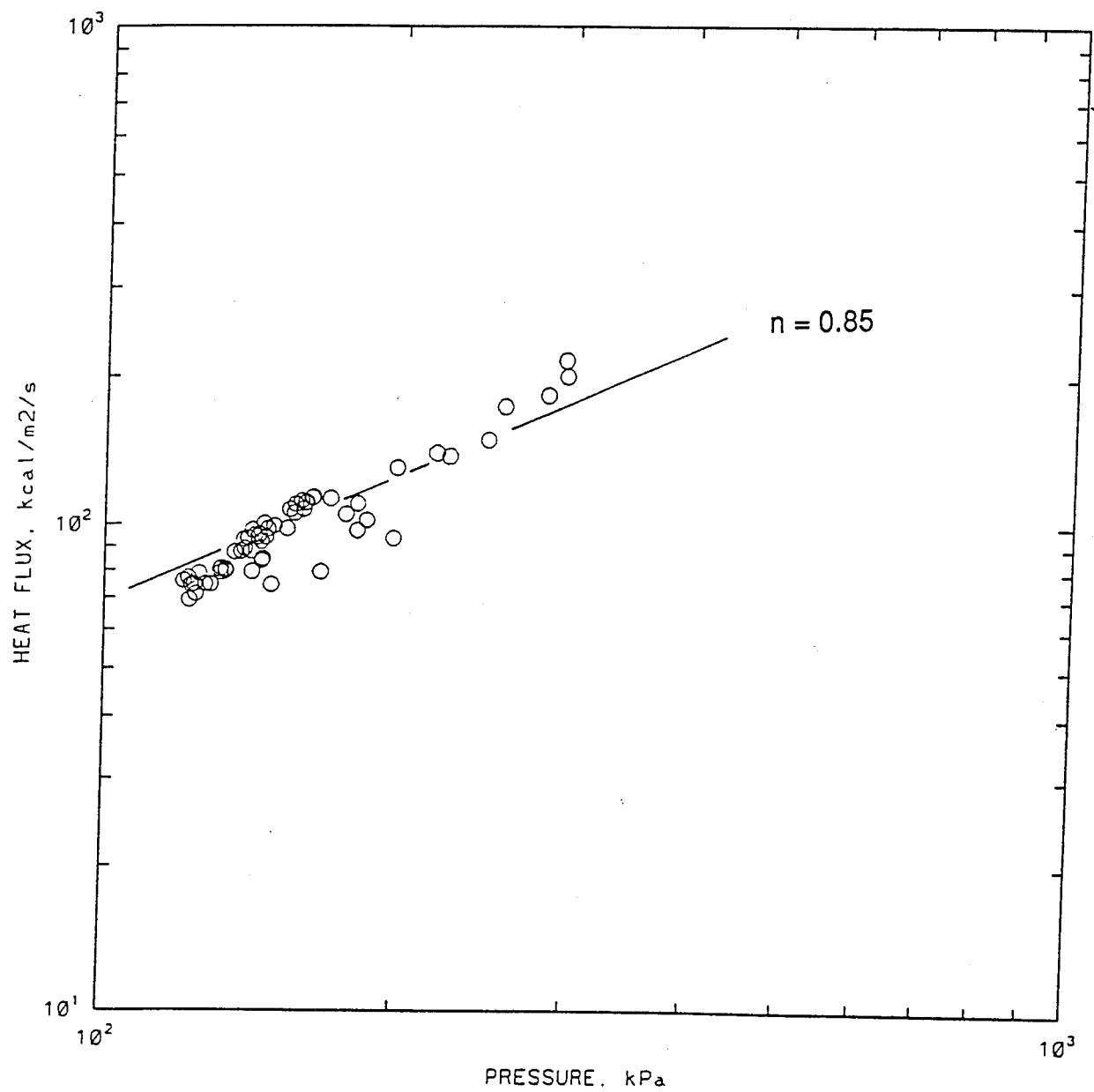


Figure 7. Power-law Correlation of KA-III, Phase C, Test C-3 TF191 Heat Flux History to Bunker Pressure History

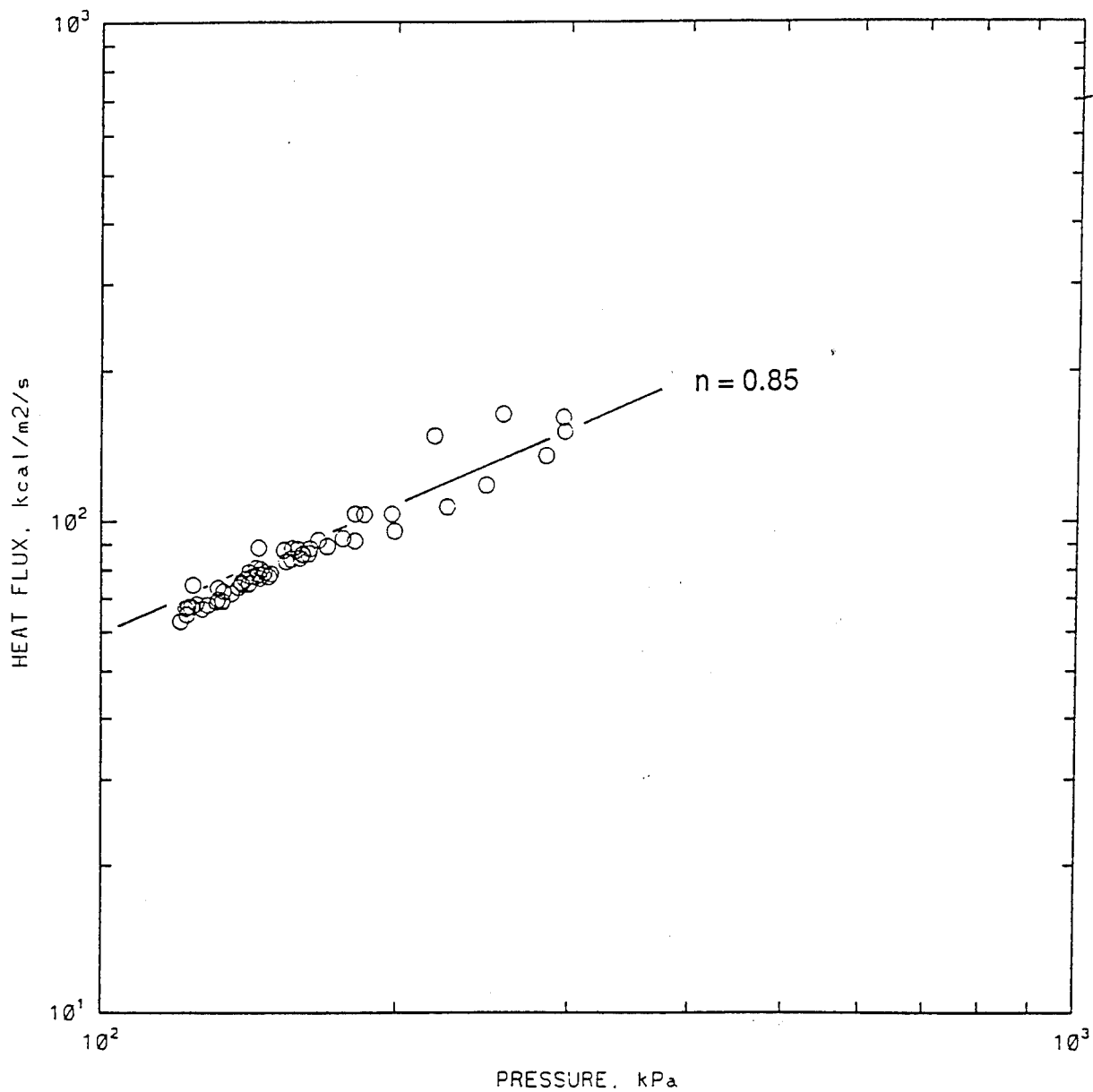


Figure 8. Power-law Correlation of KA-III, Phase C, Test C-3 TF192
Heat Flux History to Bunker Pressure History

Section 6

Recommended Instrumentation for Future Propellant Burn Tests

Based on the review and analysis presented in the prior Sections, the following recommendations are made for instrumentation to be used in future propellant burn-type tests. The recommendations are made to improve the definition of the thermal and fluid dynamic aspects of the propellant burn process with the view to enhancing the understanding and definition of the process environments, particularly the amount of energy released and where it is distributed. The recommendations are presented by a generic subdivision of the regions of interest with a rationale of the need for each measurement. Specification sheets for the recommended thermal instrumentation are given in Appendix C identifying the type and recommended supplier. And a summary of all recommended instrumentation is presented in Table 1.

Table 1: WES May '93 Propellant Burn Tests Recommended Instrumentation Summary

	Specification	Number
Chamber		
Pressures	Selected by WES	6
Total Temperature (T)	TCGT 130 Series-569	2
Total Heat Flux (HT)	TCS-E-YY-ZZ-10196	6
Radiometer (R)	32R-L-XX-140-ZZ-21096	6
Vent Pipe		
Pressures	Selected by WES	7
Total Temperature (T)	T/C-801	2
Total Heat Flux (HT)	TCS-E-YY-ZZ-10196	3
Radiometer (R)	32R-L-XX-140-ZZ-21096	3
Plume		
Pressures	Selected by WES	2+
Total Temperature (T)	T/C-801	1+
Total Heat Flux (HT)	TCS-E-YY-ZZ-10196	3
Radiometer (R)	32-L-XX-140-ZZ-21096	3

Note: Recording channels for T & HT instrumentation may require 10 MHz sampling rate.

6.1 Propellant Combustion Chamber Instrumentation

Shown in Fig. 9 is a geometrically scaled sketch of the combustion chamber hardware to be used in the WES May '93 tests with the recommended instrumentation located. The recommended instrumentation consists of gas total pressure and temperature and chamber wall total and gas radiative heat flux. The pressure instrumentation used in the KA-III, Phase C tests performed quite well and are recommended for use in the future tests. The sensing face of the transducer should be well shielded from the heat effects of gas radiation. Considering the length- to-diameter of the combustion chamber, it is recommended that three (3) pressure measurements be spaced equally along the chamber length to detect any possible gradients. The pressure measurements at each end are placed to detect any acoustical phenomena.

The gas total temperature measurements should be installed near the pressure measurements located at 0.25 and 0.75 of the chamber length. The measurement tip of the thermocouple should extend about 5 in. beyond the chamber side wall. The spec sheet for this transducer is presented as Fig. C-1 (Appendix C).

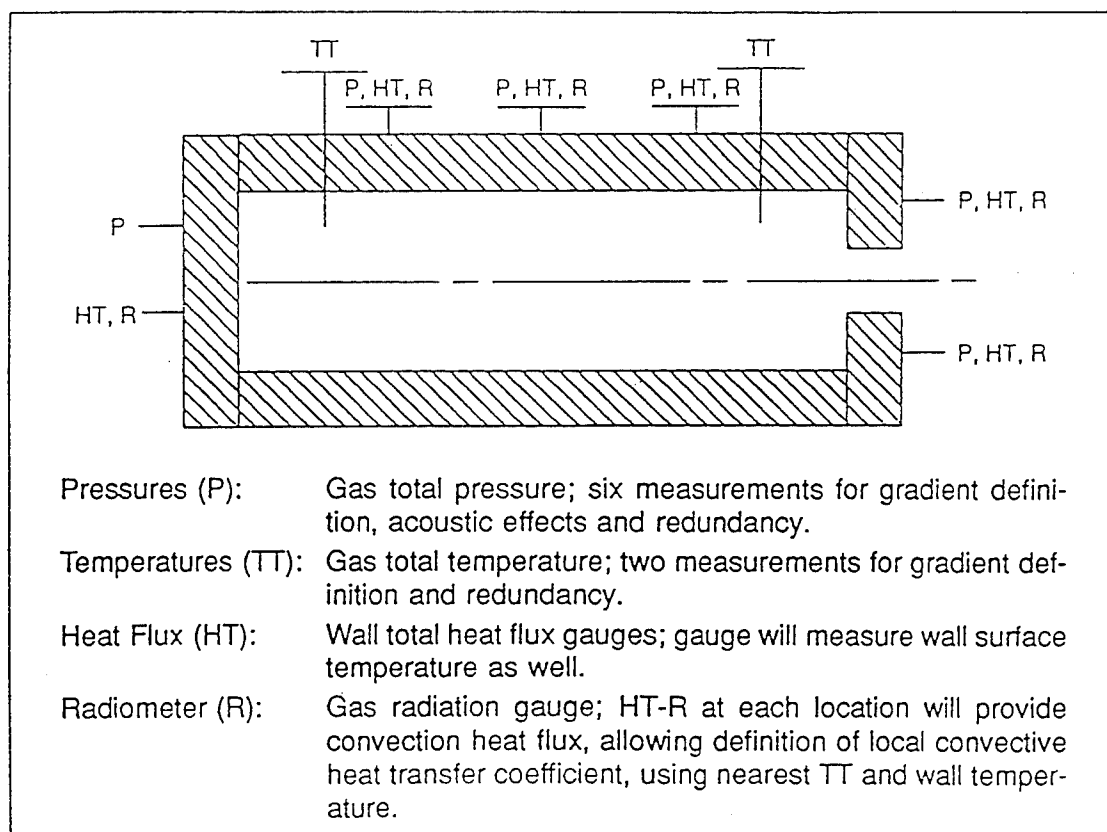


Figure 9. Recommended Instrumentation in Combustion Chamber for WES May '93 Propellant Burn Tests

Because of the indication of possible thermal lag of the thermocouple used in the KA-III, Phase C tests, the gauge of the thermocouple wire for this transducer should be as small as possible, consistent with the expected maximum temperature (1900K for the present case). If there is room in the data acquisition system, it would be desirable to add a third thermocouple of a different wire gauge near the bottom of the chamber at the same axial location as one of the top thermocouples to assess the lag effect.

The recommended heat flux measurements in the chamber are designed to allow determination of the amount of energy transferred to the walls before the gas is expelled out the vent pipe. Both total and radiative heat flux instrumentation are recommended to allow the determination of the convective heat transfer (total minus radiative), which may be used in conjunction with the simultaneous gas total and wall temperatures to compute the convective heat transfer coefficient. Having the measurements in this form provides the means to define the thermal environments for other test conditions more readily. The transducer for the total heat flux is actually a surface temperature measurement device; it was selected because it is extremely rugged, provides the direct measurement of the wall temperature, its temperature history can be used in an algorithm to determine the wall heat flux, and it is virtually impossible to overdrive its capability to define the heat flux (as was experienced in the vent pipe for Test C-4 of the KA-III, Phase C tests).

The specs sheets for the surface temperature (total heat flux) and the radiative heat flux gauges are presented as Fig. C-2 and C-3, respectively. The heat flux algorithm is discussed in Subsection 6.4: Recommended Data Reduction and Instrumentation Installation.

6.2 Vent Pipe Instrumentation

The recommended instrumentation in the vent pipe is designed to define the energy and velocity (and mass flow) of the entering and exiting flow, and the distributions with vent-pipe length of static pressure and total and radiative heat flux to the wall.. The placing of the vent-pipe instrumentation is shown in Fig. 10; the locations of the wall static pressure and heat flux transducers should be spaced logarithmically along the length for better definition of any pipe-flow characteristics the flow might exhibit.

The total and radiative heat flux gauges and total and static pressure transducers are the same as those recommended for use in the combustion chamber (See Fig. C-2 and C-3). The installation of the pressure transducers in the pitot probes (PT) is described in Subsection 6.4: Recommended Data Reduction and Instrumentation Installation.

The total temperature transducer recommended for use in the vent pipe is similar to the ones in the combustion chamber but has a different radiation shield. The specs sheet for this transducer is presented in Fig. C-4. The concerns for temperature response with thermocouple wire gauge expressed in the combustion chamber discussion apply here also.

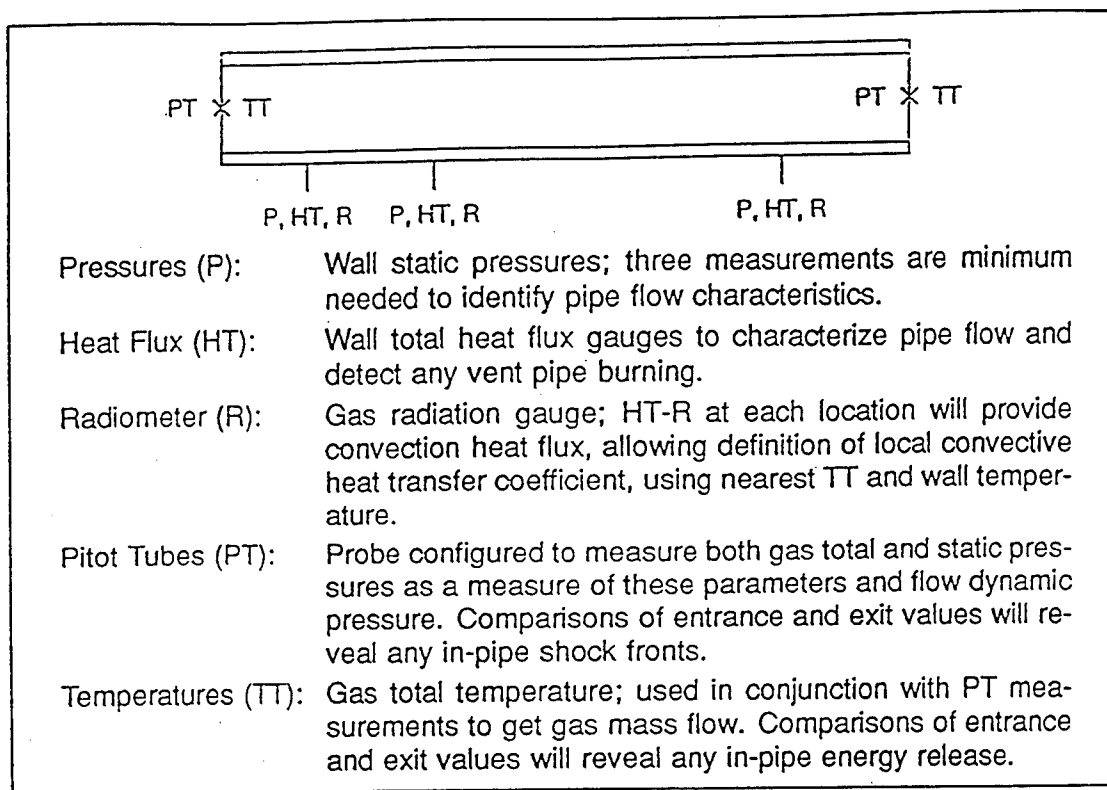


Figure 10. Recommended Instrumentation in Vent Pipe for WES
May '93 Propellant Burn Tests.

6.3 Plume Instrumentation

Shown in Fig. 11 is a layout for an instrumentation package to minimally define the thermal/fluid dynamic characteristics of the propellant burn exhaust plume. The package consists of a radiometer positioned at three locations along the plume length (15m shown) and a pitot rake which can be positioned at any location along the plume. The pitot rake should facilitate mounting pitot probes and a total temperature transducer at up to eight (8) adjustable positions both vertically and horizontally plus a center position to provide survey type measurements of the plume cross section.

The pitot probes, total temperature instruments, and the radiometers are the same as those used in the vent pipe application.

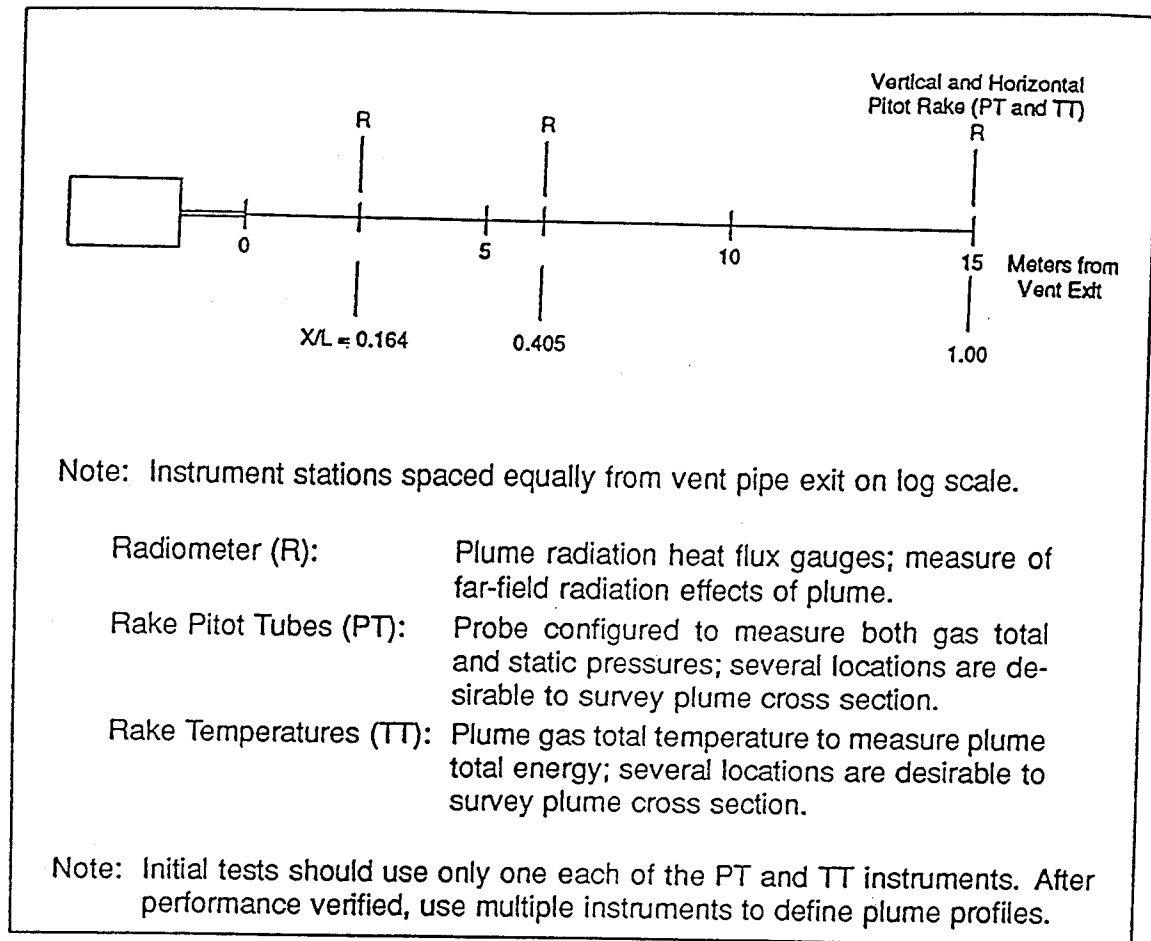


Figure 11. Recommended Instrumentation in Plume Region for WES May '93 Propellant Burn Tests.

6.4 Recommended Data Reduction and Instrumentation Installation

Data Reduction -- The total heat flux/surface temperature is the only measurement result for which the data reduction procedure is not straightforward multiplication of a gauge constant scale factor, supplied by the instrument vendor, times the instantaneous output of the instrument. Some thermocouple transducers are non-linear and require special digital data reduction.

The surface temperature is obtained by the tabular look-up in the millivolt output tables for Chromel-Constantan taking into account the thermocouple reference temperature, or input of the millivolt output into a curve fit equation of the tables. Computation of the heat flux is more complicated; it requires the time-wise integration of the surface temperature to get the heat flux.

The heat flux algorithm is based on the condition of one-dimensional conduction along the gauge, a condition that is satisfied if the gauge is installed in a material of similar thermophysical properties such that $\sqrt{\rho C_p k}$ for the gauge and the host material are as near the same as possible. For Chromel-Constantan, steel is the best match for these properties. The temperature variation of $\sqrt{\rho C_p k}$ over the range measured by the gauge is required in the data reduction procedure.

The simplest algorithms that for a gauge installed in a semi-infinite slab under a heating load from a time-invariant heat transfer coefficient. This algorithm is available in Ref [5]. However, it is not likely that the heat transfer coefficient for the conditions of the propellant burn tests will be constant with time.

A second algorithm for the time-variant heat transfer coefficient may be developed by solving the inverse of the equation presented in Ref [6] for the wall temperature as a function of the time-variant heat transfer coefficient. This approach requires the computation of the instantaneous slope of the wall temperature with time.

The most direct method of computing the heat transfer coefficient variation with time from the wall temperature time history is by the use of a one-dimensional conduction code which has this capability built in. The EXITS code, developed by REMTECH, Inc., has this capability and can be made available for use in this application.

This type gauge is recommended despite the difficult data reduction procedure required to compute the heat flux in view of the benefits of a very rugged transducer which is virtually impossible to destroy or over-range. Moreover, its use with the radiometer and gas total temperature measurement permits the computation of the convective heat transfer coefficient.

It should be emphasized here that in order to measure the total heat flux, the exposed surface of the gauge must be coated with a paint of known emissivity -- the closer to unity the better for greater accuracy.

Instrumentation Installation -- The installation requirements (hole diameter and thread type, etc.) for all the thermal instrumentation are called out on the spec sheets for each type. Additional installation considerations are discussed below.

The radiometer and heat flux gauge should be installed flush with the internal wall of the test hardware. The heat flux gauges may be contoured to the local radius. The radiometers should not be contoured and should be installed such that no part of the window is protruding into the flow.

In order to avoid the violation of thermal diffusion times, which complicates the data reduction procedure for the heat flux gauges, the minimum wall thickness into which these gauges should be installed is 1.5 in. This criterion is not satisfied in the vent pipe as it is presently designed; methods to effectively increase the local wall thickness around each gauge (1.0 in. radius) should be adopted.

The mounting of the total temperature and pitot probes in the vent pipe should be such as to minimize the interference effects of its presence in the passing flow; how much is too much is difficult to determine -- a rule of thumb is no more than 15 percent blockage area to the unblocked flow area.

The important aspect of the installation of the pressures in the pitot pressure probe is that the static pressure transducer be located sufficiently downstream of the probe front face so that the local pressure has returned to the stream static. A rule of thumb for that distance is 10 probe diameters. For all installations the pressure transducers should be protected from direct radiation from the combustion gases.

Section 7

REFERENCES

- [1] Joachim, Charles E., "KA-III' Phase C, M-1 Propellant Tests, Deflagration in Partial Confinement," Technical Report SL-91-11, U.S. Army Engineers Waterways Experiment Station, July 1991.
- [2] Freedman, Eli, "Thermodynamic Properties of Military Gun Propellants," in *Gun Propulsion Technology*, Vol. 109, *Prog. in Astro. & Aero.*, edited by Ludwig Stiefel, AIAA, Inc., Washington, DC, 1988, p. 103.
- [3] Gordon, Sanford and McBride, Bonnie J., "Computer program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations," NASA SP-273, March 1976.
- [4] Bouhard, F., Veyssi re, B., Leyer, J. -C., and Chaineaux, J., "Explosion in a Vented Vessel Connected to a Duct," in *Dynamics of Detonations and Explosions: Explosion Phenomena*, Vol. 134, *Prog. in Astro. & Aero.*, edited by A. L. Kuhl, et al., AAIA, Inc., Washington, DC, 1990, p. 85.
- [5] Cook, W. J., and Felderman, E. J., "Reduction of Data from Thin-Film Heat Transfer Gages: A Concise Numerical Technique," AAIA J., Vol. 4, No. 3, March 1966.
- [6] Goodman, T. R., "Application of Integral Methods to Transient Nonlinear Heat Transfer," *Advances in Heat Transfer*, edited by T. F. Irvine and J. P. Hartnett, Vol. 1, Academic Press, 1964.

Appendix A
ANALYSIS OF ADIABATIC BURNING
CONDITION OF M-1 PROPELLANT USED
IN KA-III, PHASE C, TESTS (CEC Code Output)

REACTANTS

C	2.0000	H	6.0000	O	1.0000	0.0000	0.0000	0.007500	-66420.00	S	298.300	F
C	6.0000	H	7.3715	N	2.6355	O	10.2715	0.0000	-164700.00	S	298.300	F
C	7.0000	H	6.0000	N	2.0000	O	4.0000	0.0000	-17100.00	S	298.300	F
C	12.0000	N	1.0000	H	11.0000	O	0.0000	0.0000	31070.00	S	298.300	F
C	16.0000	H	22.0000	O	4.0000	O	0.0000	0.049300	-201400.00	S	298.300	F
H	2.0000	O	1.0000	O	0.0000	O	0.0000	0.005000	-68315.00	S	298.300	F

NAMELISTS

```

0 *****
OKASE = 1  IDEBUG = 0  TRACE = 0.00000D+00  IONS = F  SIUNIT = F
OTP = F  HP = F  SP = F  TV = F  UV = T  SV = F  RKT = F  SHOCK = F  DETN = F
OTRNSPT = F  TRPACC = 0.999950E+00  NODATA = F
OOE = F  FA = F  FPCT = F  ERATIO = F  PHI = F
OSO = 0.0000000E+00  U = 0.0000000E+00  H = 0.0000000E+00
OV = 0.50000E+01
ORHO = 0.20000E+00
OT = 0.00000E+00

```

ONO INPT2 VALUE GIVEN FOR OF, EQRT, FA, OR FPCT

OMIX = 0.00000E+00

OSPECIES BEING CONSIDERED IN THIS SYSTEM

J 3/78	C	J12/67	CH	J12/72	CH2	J 3/61	FORMALDEHYDE	J 3/61	FORMALDEHYDE	J 3/61	FORMIC ACID
J 6/69	CH3	L 9/85	HYDROXYMETHYLENE	L 9/85	METHYLOXIDE	L 5/84	CH4	L 5/84	METHANOL	L 4/85	METHANOL
J 6/69	CN	J12/70	C2H RAD	J 6/66	CNN RAD	J 9/65	CO	J 9/65	CO2	J 9/65	CO2
J12/69	C2	J 3/67	C2H RAD	J 3/61	ACETYLENE	BUR 84	KETENE	BUR 84	C2H3 RAD	BUR 84	C2H3 RAD
BUR 84	METHYL CYANIDE	BUR 84	CH3CO RAD	BUR 84	CH2CHO RAD	BUR 84	ETHYLENE	BUR 84	ACETALDEHYDE	BUR 84	ACETALDEHYDE
L 4/85	ACETIC ACID	L 4/85	(FORMIC ACID)2	P10/83	ETHYL RAD	BUR 84	ETHYL OXIDE RAD	L 5/84	ETHANE	L 5/84	ETHANE
BUR 84	AZOMETHANE	BUR 84	DIMETHYL ETHER	BUR 84	ETHANOL	J 3/67	CNC RAD	J 3/61	CYANOGEN	J 3/61	CYANOGEN
J 9/66	CCO RAD	J12/69	C3	DB6/61	C3H3 RAD	BUR 84	CYCLOPROPENE	BUR 84	PROPYLENE	BUR 84	PROPYLENE
BUR 84	ALLENE	BUR 84	C3H5 RAD	BUR 84	CYCLOPROPANE	L 4/85	PROPYLENE	L 9/85	PROPYLENE OXIDE	L 9/85	PROPYLENE OXIDE
L 9/85	I-PROPYL RAD	L 9/85	N-PROPYL RAD	L 4/85	PROPANE	L 1/84	1-PROPANOL	L 9/85	CARBON SUBOXIDE	L 9/85	CARBON SUBOXIDE
J12/69	C4	BUR 84	BUTADIENE	P10/85	CYCLOBUTADIENE	BUR 84	BUTAN-1EN-3YN	P 4/84	1,3-BUTADIENE	P 4/84	1,3-BUTADIENE
BUR 84	2-BUTYNE	BUR 84	2-BUTENE TRANS	BUR 84	2-BUTENE CIS	BUR 84	ISOBUTENE	BUR 84	1-BUTENE	BUR 84	1-BUTENE
L 4/85	(ACETIC ACID)2	L 9/85	T-BUTYL RAD	L 9/85	S-BUTYL RAD	P10/83	N-BUTYL RAD	L 4/85	N-BUTANE	L 4/85	N-BUTANE
L 4/85	ISOBUTANE	J 3/61	CARBON SUBNITRID	J12/69	C5	P10/85	CYCLOPENTADIENE	P12/52	CYCLOPENTANE	P12/52	CYCLOPENTANE
P12/52	1-PENTENE	L 5/87	T-PENTYL RAD	P10/83	N-PENTYL RAD	P10/85	PENTANE	P10/85	ISOPENTANE	P10/85	ISOPENTANE
P10/85	CH3C(CH3)2CH3	BUR 84	HEXATRIENE	L12/84	PHENYL RAD	L12/84	PHENOXY RAD	L12/84	BENZENE	L12/84	BENZENE
L12/84	PHENOL	BUR 84	CYCLOHEXENE	P10/83	N-HEXYL RAD	P10/84	TOLUENE	L 6/87	CRESOL	L 6/87	CRESOL
P12/52	1-HEPTENE	BUR 84	N-HEPTYL RAD	P 4/81	N-HEPTANE	P12/52	1-OCTENE	P10/83	N-OCTYL RAD	P10/83	N-OCTYL RAD
P 4/85	OCTANE	P 4/85	ISO-OCTANE	P10/83	N-HEPTYL RAD	BUR 84	NAPHTHLENE	BUR 84	AZULENE	BUR 84	AZULENE
P10/83	N-DECYL RAD	L12/84	O-BIPHENYL RAD	L12/84	BIPHENYL	L 6/88	JET-A(G)	J 3/77	H	J 3/77	H
L12/69	HCN	J12/70	HCO RAD	J12/70	HNCO	RUS 78	HNO	RUS 78	HNO2	RUS 78	HNO2
RUS 78	HNO3	L 5/89	HO2	J 3/77	H2	J12/65	H2N2	J 3/79	H2O	J 3/79	H2O
L 3/85	H2O2	J 3/77	N	RUS 78	NCO	RUS 78	NH	RUS 78	NH2	RUS 78	NH2
J 6/77	NH3	RUS 78	NH2OH	RUS 78	NO	J12/64	NO2	J12/64	NO3	J12/64	NO3

RUS 78 N2O
RUS 78 N3H
J 3/78 C(GR)
L 3/81 H2O(S)

RUS 78 N2H4
RUS 78 N3
J 6/61 O3
L 6/88 JET-A(L)

RUS 78 NH2NO2
RUS 78 N2O5
J 3/77 O2
P10/80 OCTANE(L)

RUS 78 N2H2
RUS 78 N2O4
J 6/77 OH
P10/80 TOLUENE(L)

J 3/77 N2
RUS 78 N2O3
J 3/77 O
P10/80 BENZENE(L)
J 3/79 H2O(L)
DOF = 0.000000

INTERNAL ENERGY
(KG-MOL) (DEG K)/KG
OKG-FORM.WT./KG

EFFECTIVE FUEL
HPP(1)
-0.28176266E+03
BOP(I,2)
0.25349588E-01
0.31067750E-01
0.33694333E-01
0.893330269E-02

EFFECTIVE OXIDANT
HPP(1)
0.00000000E+00
BOP(I,1)
0.00000000E+00
0.00000000E+00
0.00000000E+00
0.00000000E+00
0.00000000E+00

MIXTURE
HSUBO
-0.28176266E+03
BOP(I)
0.25349588E-01
0.31067750E-01
0.33694333E-01
0.893330269E-02

POINT ITN T C
1 13 2437.49 -6.380
-7.089 -20.535 -11.217
THERMODYNAMIC EQUILIBRIUM COMBUSTION PROPERTIES AT ASSIGNED VOLUME

CASE NO. 1

CHEMICAL FORMULA

FUEL C 2.00000 H 6.00000 O 1.00000
FUEL C 6.00000 H 7.37150 N 2.63550 O 10.27150
FUEL C 7.00000 H 6.00000 N 2.00000 O 4.00000
FUEL C 12.00000 N 1.00000 H 11.00000
FUEL C 16.00000 H 22.00000 O 4.00000
FUEL H 2.00000 O 1.00000
O/F = 0.0000 PERCENT FUEL = 100.0000 EQUIVALENCE RATIO = 1.9657 PHI = 0.0000

WT FRACTION
(SEE NOTE)
0.007444 -66420.000 S
0.831166 -164700.000 S
0.097667 -17100.000 S
0.009826 31070.000 S
0.048933 -201400.000 S
0.004963 -68315.000 S

ENERGY CAL/MOL

TEMP DEG K

OTHERMODYNAMIC PROPERTIES

P, ATM 1810.19
T, DEG K 2437.49
RHO, G/CC 2.0000-1
H, CAL/G -340.73
U, CAL/G -559.92
G, CAL/G -5703.39
S, CAL/(G) (K) 2.2001
M, MOL WT 22.099
(DLV/DLP) T -1.00334
(DLV/DLP) P 1.0150
CP, CAL/(G) (K) 0.4475
GAMMA (S) 1.2558
SON VEL, M/SEC 1073.2

OMOLE FRACTIONS

FORMALDEHYDE 0.00011
FORMIC ACID 0.00005
CH3 0.00001
CH4 0.00053

CO 0.50555
 CO2 0.05351
 H 0.00020
 HCN 0.00036
 HCO RAD 0.00003
 HNCO 0.00003
 H2 0.20902
 H2O 0.13174
 NH3 0.00063
 N2 0.09819
 OH 0.00003

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS

C	CH	CH2	HYDROXYMETHYLENE	METHYLOXIDE	METHANOL	CN
NCN RAD	CNN RAD	C2	C2H RAD	ACETYLENE	KETENE	C2H3 RAD
METHYL CYANIDE	CH3CO RAD	CH2CHO RAD	ETHYLENE	ACETALDEHYDE	ACETIC ACID	(FORMIC ACID)2
ETHYL RAD	ETHYL OXIDE RAD	ETHANE	AZOMETHANE	DIMETHYL ETHER	ETHANOL	CNC RAD
CYANOGEN	CCO RAD	C3	C3H3 RAD	CYCLOPROPENE	PROPYLENE	ALLENE
C3H5 RAD	CYCLOPROPANE	PROPYLENE	PROPYLENE OXIDE	I-PROPYL RAD	N-PROPYL RAD	PROPANE
1-PROPANOL	CARBON SUBOXIDE	C4	BUTADIENE	CYCLOBUTADIENE	BUTAN-1EN-3YN	1,3-BUTADIENE
2-BUTYNE	2-BUTENE TRANS	2-BUTENE CIS	ISOBUTENE	1-BUTENE	(ACETIC ACID)2	T-BUTYL RAD
S-BUTYL RAD	N-BUTYL RAD	N-BUTANE	ISOBUTANE	CARBON SUBNITRID	C5	CYCLOPENTADIENE
CYCLOPENTANE	1-PENTENE	T-PENTYL RAD	N-PENTYL RAD	PENTANE	ISOPENTANE	CH3C(CH3)2CH3
HEXATRIENE	PHENYL RAD	PHENOXY RAD	BENZENE	PHENOL	CYCLOHEXENE	N-HEXYL RAD
TOLUENE	CRESOL	1-HEPTENE	N-HEPTYL RAD	N-HEPTANE	1-OCTENE	N-OCTYL RAD
OCTANE	ISO-OCTANE	N-NONYL RAD	NAPHTHLENE	AZULENE	N-DECYL RAD	O-BIPHENYL RAD
BIPHENYL	JET-A (G)	HNO	HNO2	HNO3	HO2	H2N2
H2O2	N	NCO	NH	NH2	NH2OH	NO
NO2	NO3	N2H2	NH2NO2	N2H4	N2O	N2O3
N2O4	N2O5	N3	N3H	O	O2	O3
C (GR)	BENZENE (L)	TOLUENE (L)	OCTANE (L)	JET-A (L)	H2O (S)	H2O (L)

NOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS

1 STOP
 ERROR IN ABOVE CARD. CONTENTS IGNORED.

Appendix B
ANALYSIS OF ISENTROPIC BURNING
CONDITION OF M-1 PROPELLANT USED
IN KA-III, PHASE C, TESTS (CEC Code Output)

REACTANTS
 C 2.0000 H 6.0000 O 1.0000 0.0000 0.007500 -66420.00 298.300 F
 C 6.0000 H 7.3715 N 2.6355 O 10.2715 0.0000 0.837400 -164700.00 298.300 F
 C 7.0000 H 6.0000 N 2.0000 O 4.0000 0.0000 0.098400 -17100.00 298.300 F
 C 12.0000 N 1.0000 H 11.0000 0.0000 0.009900 31070.00 298.300 F
 C 16.0000 H 22.0000 O 4.0000 0.0000 0.049300 -201400.00 298.300 F
 H 2.0000 O 1.0000 0.0000 0.0000 0.005000 -68315.00 298.300 F

NAMELISTS

0 ***INPT2***

OKASE = 1 IDEBUG = 0 TRACE = 0.00000D+00 IONS = F SIUNIT = F
 OTP = F HP = F SP = F TV = F UV = F SV = F RKT = T SHOCK = F DETN = F
 OTNSPT = F TRFACC = 0.999950E+00 NODATA = F
 OOF = F FA = F FPCT = F ERATIO = F PHI = F
 OSO = 0.0000000E+00 U = 0.0000000E+00 H = 0.0000000E+00
 OP = 0.15000E+02
 OT = 0.00000E+00

ONC INPT2 VALUE GIVEN FOR OF, EQRAT, FA, OR FECT

OMIX = 0.00000E+00

OSPECIES BEING CONSIDERED IN THIS SYSTEM

J 3/78 C J12/67 CH J12/72 CH2
 J 6/69 CH3 L 9/85 HYDROXYMETHYLENE L 9/85 METHYL OXIDE
 J 6/69 CN J12/70 CN RAD L 9/85 METHYL OXIDE
 J12/69 C2 J 3/67 C2H RAD J 3/61 ACETYLENE
 BUR 84 METHYL CYANIDE BUR 84 CH3O RAD BUR 84 CH2CHO RAD
 L 4/85 ACETIC ACID L 4/85 (FORMIC ACID) 2 P10/83 ETHYL RAD
 BUR 84 AZOMETHANE BUR 84 DIMETHYL ETHER BUR 84 ETHANOL
 J 9/66 CCO RAD J12/69 C3 DB6/61 C3H3 RAD
 BUR 84 ALLENE BUR 84 C3H5 RAD BUR 84 CYCLOPROPANE
 L 9/85 I-PROPYL RAD L 9/85 N-PROPYL RAD L 4/85 PROPANE
 J12/69 C4 BUR 84 BUTADIENE L 1/84 1-PROPANOL
 BUR 84 2-BUTYNE BUR 84 2-BUTENE TRANS BUR 84 2-BUTENE CIS
 L 4/85 (ACETIC ACID) 2 L 9/85 T-BUTYL RAD
 L 4/85 ISOBUTANE J 3/61 CARBON SUBNITRID S-BUTYL RAD
 P12/52 1-PENTENE L 5/87 T-PENTYL RAD C5
 P10/85 CH3C(CH3)2CH3 BUR 84 HEXATRIENE N-PENTYL RAD
 L12/84 PHENOL BUR 84 CYCLOHEXENE P10/84 PHENYL RAD
 P12/52 1-HEPTENE P10/83 N-HEPTYL RAD P10/83 N-HEPTANE
 P 4/85 OCTANE P 4/85 ISO-OCTANE P10/83 N-NONYL RAD
 P10/83 N-DECYL RAD L12/84 O-BIPHENYL RAD
 L12/69 HCN J12/70 HCO RAD L12/84 BIPHENYL
 RUS 78 HNO3 L 5/89 HO2 J 3/77 H2
 L 3/85 H2O2 J 3/77 N J12/70 NCO
 J 6/77 NH3 RUS 78 NH2OH RUS 78 NO
 J 3/77 N2 RUS 78 N2H2 RUS 78 NH2NO2

J 3/61 FORMALDEHYDE
 L 5/84 CH4
 J 9/65 CO
 BUR 84 KETENE
 L 4/85 ETHYLENE
 BUR 84 ETHYL OXIDE RAD
 J 3/67 CNC RAD
 BUR 84 CYCLOPROPENE
 L 4/85 PROPYLENE
 L 1/84 1-PROPANOL
 BUR 84 BUTAN-1EN-3YN
 BUR 84 ISOBUTENE
 P10/83 N-BUTYL RAD
 P10/85 CYCLOPENTADIENE
 P10/85 PENTANE
 L12/84 PHENOXY RAD
 P10/84 TOLUENE
 P12/52 1-OCTENE
 BUR 84 NAPHTHLENE
 L 6/88 JET-A (G)
 RUS 78 HNO
 J12/65 H2N2
 RUS 78 NH
 RUS 78 NO2
 RUS 78 N2H4

L 4/85 FORMIC ACID
 L 9/85 METHANOL
 J 9/65 CO2
 BUR 84 C2H3 RAD
 BUR 84 ACETALDEHYDE
 L 5/84 ETHANE
 J 3/61 CYANOGEN
 BUR 84 PROPYLENE
 L 9/85 PROPYLENE OXIDE
 J 6/68 CARBON SUBOXIDE
 P 4/84 1,3-BUTADIENE
 BUR 84 1-BUTENE
 L 4/85 N-BUTANE
 P12/52 CYCLOPENTANE
 P10/85 ISOPENTANE
 L12/84 BENZENE
 L 6/87 CRESOL
 P10/83 N-OCTYL RAD
 BUR 84 AZULENE
 J 3/77 H
 RUS 78 HNO2
 J 3/79 H2O
 RUS 78 NH2
 J12/64 NO3
 RUS 78 N2O

RUS 78 N203
J 3/77 O
P10/80 BENZENE(L)
J 3/79 H2O(L)
RUS 78 N204
J 6/77 OH
P10/80 TOLUENE(L)
RUS 78 N205
J 3/77 O2
P10/80 OCTANE(L)
RUS 78 N3
J 6/61 O3
L 6/88 JET-A(L)
RUS 78 N3H
J 3/78 C(GR)
L 3/81 H2O(S)

0 ***RKTIME***
OEQL = T FROZ = T NFZ = 1 TCEST = 3800.000 FAC = F MA = 0.00000000E+00 ACAT = 0.00000000E+00 DEBUGF = F
OPCP = 0.10204000E+01
OSUBAR =
OSUPAR =
OOF = 0.000000

ENTHALPY
(KG-MOL) (DEG K) /KG
OKG-FORM.WT./KG
C
H
O
N
OPOINT ITN T C
1 21 1927.03 -11.497
2 4 1703.22 -10.657
PC/PT= 1.808481 T = 1703.22
2 2 1702.49 -10.654
PC/PT= 1.812162 T = 1702.49
3 4 1919.02 -11.472
1
THEORETICAL ROCKET PERFORMANCE ASSUMING EQUILIBRIUM COMPOSITION DURING EXPANSION
FROM INFINITE AREA COMBUSTOR

OPINE = 15.0 PSIA
CASE NO. 1

CHEMICAL FORMULA
FUEL C 2.00000 H 6.00000 O 1.00000
FUEL C 6.00000 H 7.37150 N 2.63550 O 10.27150
FUEL C 7.00000 H 6.00000 N 2.00000 O 4.00000
FUEL C 12.00000 N 1.00000 H 11.00000
FUEL C 16.00000 H 22.00000 O 4.00000
FUEL H 2.00000 O 1.00000
O/F= 0.0000 PERCENT FUEL= 100.0000 EQUIVALENCE RATIO= 1.9657 PHI= 0.0000
0 CHAMBER THROAT EXIT
PINE/P 1.0000 1.8122 1.0204
P, ATM 1.0207 0.56324 1.0003
T, DEG K 1927.03 1702.49 1919.02
RHO, G/CC 1.4230-4 8.8898-5 1.4004-4
H, CAL/G -559.92 -657.06 -563.42
U, CAL/G -733.63 -810.50 -736.41
G, CAL/G -5904.06 -5378.49 -5885.34
S, CAL/(G) (K) 2.7732 2.7732 2.7732
M, MOL WT 22.046 22.050 22.046
(DLV/DLP) T -1.00012 -1.00003 -1.00011
(DLV/DLP) P 1.0034 1.0008 1.0032

CP, CAL/(G) (K) 0.4387 0.4293 0.4382
GAMMA (S) 1.2606 1.2662 1.2609
SON VEL,M/SEC 957.2 901.6 955.3
MACH NUMBER 0.000 1.000 0.179

OPERFORMANCE PARAMETERS

AE/AT 1.0000 3.3440
CSTAR, FT/SEC 4233 4233
CF 0.699 0.133
IVAC, LB-SEC/LB 164.5 448.7
ISP, LB-SEC/LB 91.9 17.5

OMOLE FRACTIONS

CO 0.49571 0.48821 0.49549
CO2 0.06313 0.07074 0.06336
H 0.00045 0.00010 0.00043
H2 0.22141 0.22921 0.22165
H2O 0.12081 0.11326 0.12058
N2 0.09847 0.09848 0.09847
OH 0.00002 0.00000 0.00002

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS

C	CH	CH2	FORMALDEHYDE	FORMIC ACID	CH3	HYDROXYMETHYLENE
	METHYLOXIDE	METHANOL	CN	NCN RAD	CNN RAD	C2
	C2H RAD	KETENE	C2H3 RAD	METHYL CYANIDE	CH3CO RAD	CH2CHO RAD
	ETHYLENE	ACETIC ACID	(FORMIC ACID)2	ETHYL RAD	ETHYL OXIDE RAD	ETHANE
	AZOMETHANE	ETHANOL	CNC RAD	CYANOGEN	CCO RAD	C3
	C3H3 RAD	PROPYLENE	ALLENE	C3H5 RAD	CYCLOPROPANE	PROPYLENE
	PROPYLENE OXIDE	N-PROPYL RAD	PROPANE	1-PROPANOL	CARBON SUBOXIDE	C4
	BUTADIENE	BUTAN-1EN-3YN	1,3-BUTADIENE	2-BUTYNE	2-BUTENE TRANS	2-BUTENE CIS
	ISOBUTENE	(ACETIC ACID)2	T-BUTYL RAD	S-BUTYL RAD	N-BUTYL RAD	N-BUTANE
	ISOBUTANE	C5	CYCLOPENTADIENE	CYCLOPENTANE	1-PENTENE	T-PENTYL RAD
	N-PENTYL RAD	ISOPENTANE	CH3C(CH3)2CH3	HEXATRIENE	PHENYL RAD	PHENOXY RAD
	BENZENE	CYCLOHEXENE	N-HEXYL RAD	TOLUENE	CRESOL	1-HEPTENE
	N-HEPTYL RAD	1-OCTENE	N-OCTYL RAD	OCTANE	ISO-OCTANE	N-NONYL RAD
	NAPHTHLENE	AZULENE	O-BIPHENYL RAD	BIPHENYL	JET-A(G)	HCN
	HCO RAD	HNCO	HNO2	HNO3	HO2	H2N2
	H2O2	N	NH	NH2	NH3	NH2OH
	NO	NO2	N2H2	NH2NO2	N2H4	N2O
	N2O3	N2O4	N3	N3H	O	O2
	O3	C(GR)	TOLUENE (L)	OCTANE (L)	JET-A (L)	H2O (S)
	H2O (L)	BENZENE (L)				

ONOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS
1 THEORETICAL ROCKET PERFORMANCE ASSUMING FROZEN COMPOSITION DURING EXPANSION

OPINF = 15.0 PSIA
CASE NO. 1

CHEMICAL FORMULA

WT FRACTION ENERGY STATE TEMP
(SEE NOTE) CAL/MOL DEG K

FUEL	C	2.00000	H	6.00000	O	1.00000	0.007444	-66420.000	298.30
FUEL	C	6.00000	H	7.37150	N	2.63550	0.831166	-164700.000	298.30
FUEL	C	7.00000	H	6.00000	N	2.00000	0.097667	-17100.000	298.30
FUEL	C	12.00000	N	1.00000	H	11.00000	0.009826	31070.000	298.30
FUEL	C	16.00000	H	22.00000	O	4.00000	0.048933	-201400.000	298.30
FUEL	H	2.00000	O	1.00000			0.004963	-68315.000	298.30

0 O/F= 0.0000 PERCENT FUEL= 100.0000 EQUIVALENCE RATIO= 1.9657 PHI= 0.0000

0 CHAMBER THROAT EXIT

PINF/P 1.0000 1.8199 1.0204

P, ATM 1.0207 0.56085 1.0003

T, DEG K 1927.03 1693.47 1918.73

RHO, G/CC 1.4230-4 8.8975-5 1.4006-4

H, CAL/G -559.92 -657.52 -563.42

U, CAL/G -733.63 -810.17 -736.38

G, CAL/G -5904.06 -5353.93 -5884.54

S, CAL/(G) (K) 2.7732 2.7732 2.7732

M, MOL WT 22.046 22.046 22.046

CP, CAL/(G) (K) 0.4218 0.4136 0.4215

GAMMA (S) 1.2718 1.2787 1.2720

SON VEL, M/SEC 961.4 903.7 959.4

MACH NUMBER 0.000 1.000 0.178

OPERFORMANCE PARAMETERS

AE/AT 1.0000 3.3544

CSTAR, FT/SEC 4220 4220

CF 0.703 0.133

IVAC, LB-SEC/LB 164.2 448.6

ISP, LB-SEC/LB 92.2 17.5

OMOLE FRACTIONS

CO	0.49571	CO2	0.06313	H	0.00045	H2	0.22141
H2O	0.12081	N2	0.09847	OH	0.00002		

ADDITIONAL PRODUCTS WHICH WERE CONSIDERED BUT WHOSE MOLE FRACTIONS WERE LESS THAN 0.50000E-05 FOR ALL ASSIGNED CONDITIONS

C	CH	CH2	CH3	FORMIC ACID	HCN	HYDROXYMETHYLENE
METHYLOXIDE	METHANOL	KETENE	CN	NCN RAD	CNN RAD	C2
C2H RAD	ACETYLENE	ACETIC ACID	C2H3 RAD	METHYL CYANIDE	CH3CO RAD	CH2CHO RAD
ETHYLENE	ACETALDEHYDE	ETHANOL	(FORMIC ACID)2	ETHYL RAD	ETHYL OXIDE RAD	ETHANE
AZOMETHANE	DIMETHYL ETHER	PROPYLENE	CNC RAD	CYANOGEN	CCO RAD	C3
C3H3 RAD	CYCLOPROPENE	N-PROPYL RAD	ALLIENE	C3H5 RAD	CYCLOPROPANE	PROPYLENE
PROPYLENE OXIDE	I-PROPYL RAD	CYCLOBUTADIENE	PROPANE	1-PROPANOL	CARBON SUBOXIDE	C4
BUTADIENE	CYCLOBUTADIENE	BUTAN-1EN-3YN	1,3-BUTADIENE	2-BUTYNE	2-BUTENE TRANS	2-BUTENE CIS
ISOBUTENE	1-BUTENE	(ACETIC ACID)2	T-BUTYL RAD	S-BUTYL RAD	N-BUTYL RAD	N-BUTANE
ISOBUTANE	CARBON SUBNITRID	C5	CYCLOPENTADIENE	CYCLOPENTANE	1-PENTENE	T-PENTYL RAD
N-PENTYL RAD	PENTANE	ISOPENTANE	CH3C(CH3)2CH3	HEXATRIYNE	PHENYL RAD	PHENOXY RAD
BENZENE	PHENOL	CYCLOHEXENE	N-HEXYL RAD	TOLUENE	CRESOL	1-HEPTENE
N-HEPTYL RAD	N-HEPTANE	1-OCTENE	N-OCTYL RAD	OCTANE	ISO-OCTANE	N-NONYL RAD
NAPHTHYLENE	AZULENE	N-DECYL RAD	O-BIPHENYL RAD	BIPHENYL	JET-A (G)	HCN
HCO RAD	HNCO	HNO	HNO2	HNO3	HO2	H2N2

H2O2	N	NCO	NH	NH2	NH3	NH2OH
NO	NO2	NO3	N2H2	NH2NO2	N2H4	N2O
N2O3	N2O4	N2O5	N3	N3H	O	O2
O3	C (GR)	BENZENE (L)	TOLUENE (L)	OCTANE (L)	JET-A (L)	H2O (S)
H2O (L)						

ONOTE. WEIGHT FRACTION OF FUEL IN TOTAL FUELS AND OF OXIDANT IN TOTAL OXIDANTS

1 STOP

Appendix C
SPECIFICATION SHEETS FOR THE
RECOMMENDED THERMAL INSTRUMENTATION

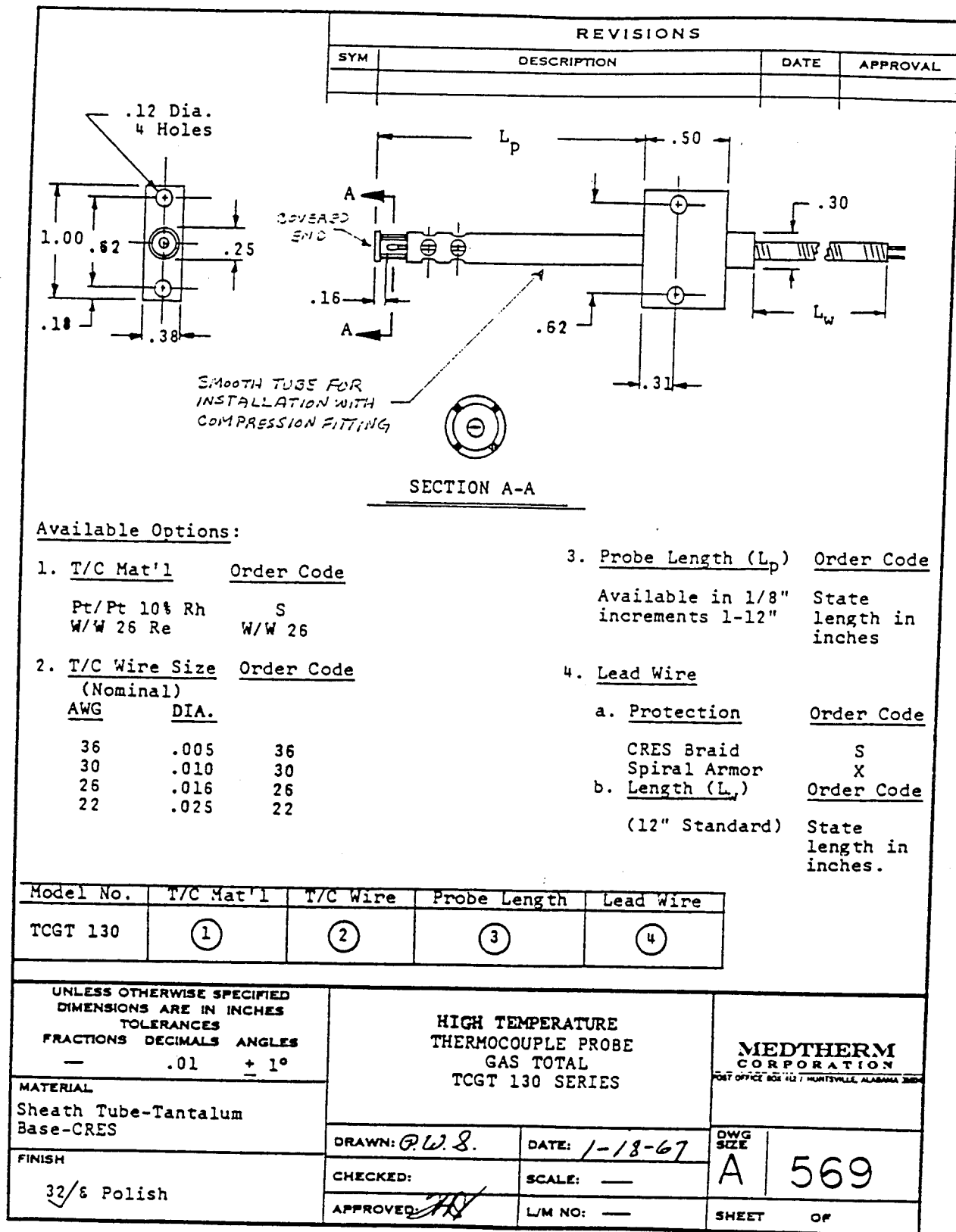


Figure C-1: Recommended Chamber Total Temperature Instrumentation
for WES May '93 Propellant Burn Tests

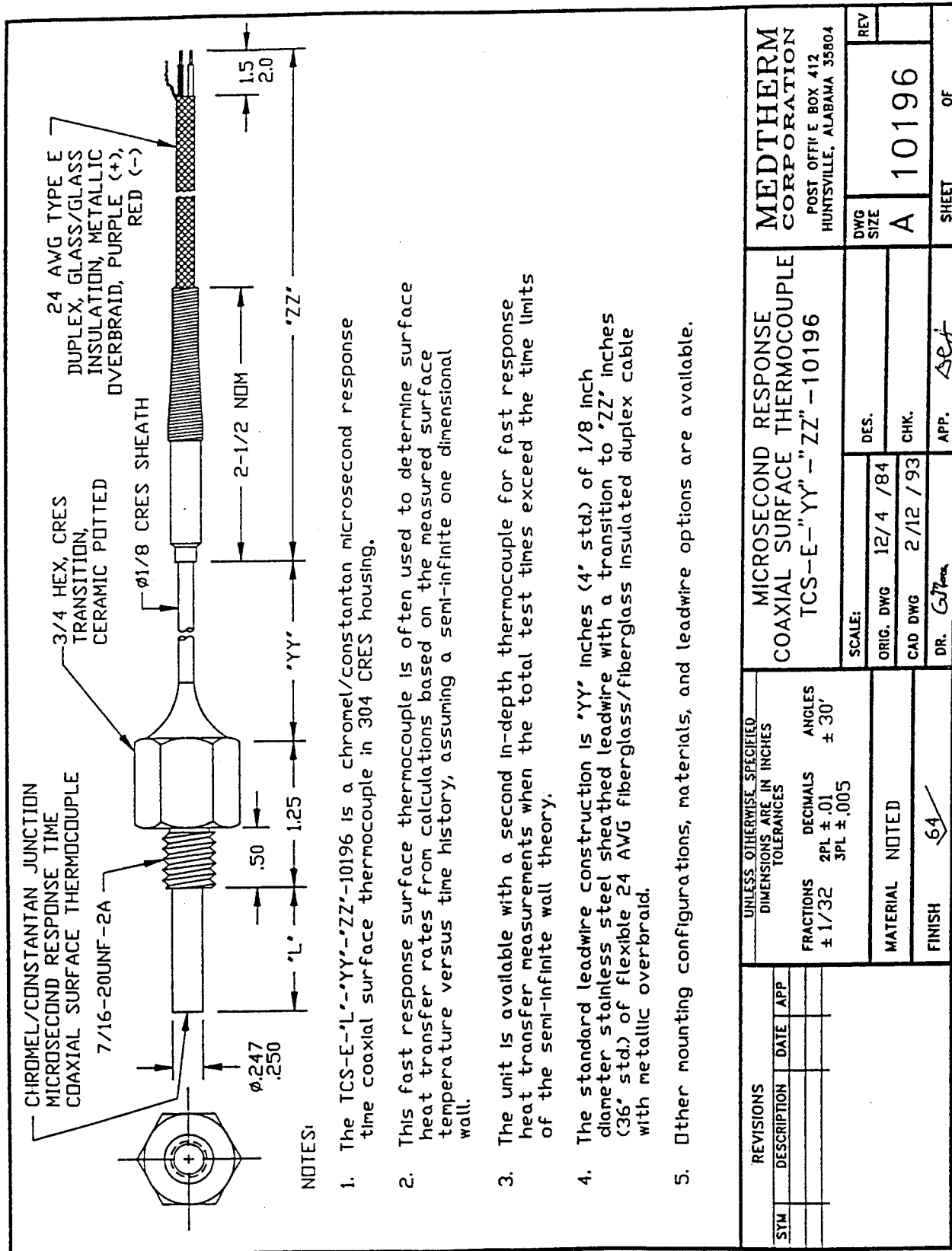
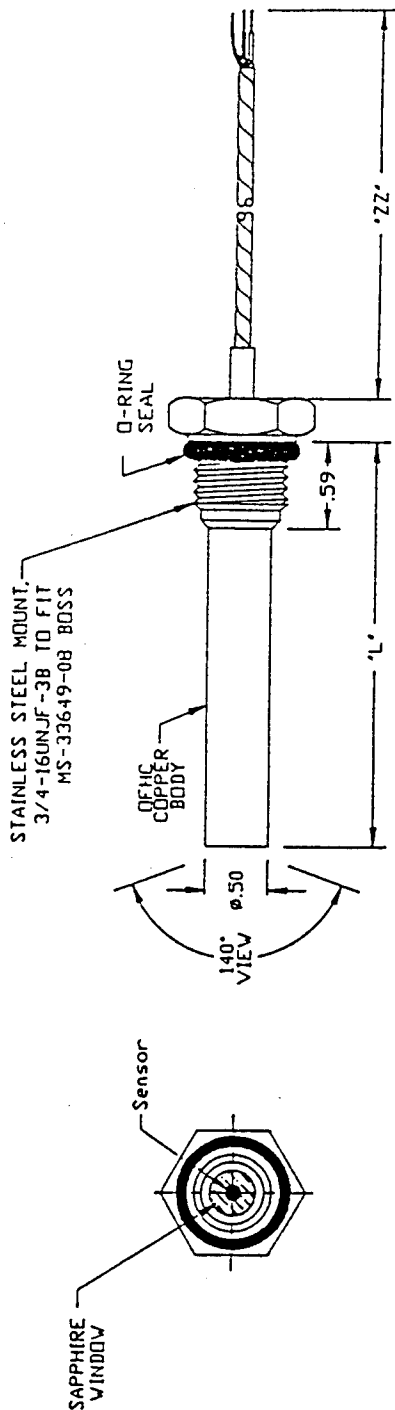


Figure C-2: Recommended Total Heat Flux/Surface Thermocouple Instrumentation
for WES May '93 Propellant Burn Tests



NOTES:

1. The 32R-"L"-XX"-140-"ZZ"-21096 is an infrared radiometer with sapphire window and 140° view angle. The radiometer will provide a linear output directly proportional to the incident radiant flux within the 0.3 to 5.5 micron spectral passband of the window. The standard nominal output is 10 millivolts at the design heat flux level "XX" in Btu/ft²sec. Other outputs are available. Each unit is supplied with a certified calibration traceable to NIST.
2. The unit is designed to operate at pressures to 3000 psi.
3. The lead wire construction consist of "ZZ" inches of 24 AVG stranded nickel plated copper duplex wire with teflon over each conductor (White positive, Black negative), nickel plated copper braid over both, teflon jacket overall.
4. To order, specify Model No. by replacing drawing notation dimensions with the appropriate dimensions, in inches, to meet specific installation requirements.

"L" - Length of Ø.50 sensing tip, inches

"XX" - Design heat flux level, BTU/ft²sec

"ZZ" - Flexible lead wire length, inches

UNLESS OTHERWISE SPECIFIED		INFRARED RADIOMETER		MEDTHERM CORPORATION	
FRACTIONS	± 1/32	DES.	1 /	DWG SIZE	B
TOLERANCES	± .015	ORIG. DWG	2/28/93	REV	
DECIMALS	± .005	CAD DWG			
ANGLES	± 30°	APP.			
MATERIAL		NOTED		SHEET 21096 OF	
FINISH					
		32R-"L"-XX"-140-"ZZ"-21096		POST OFFICE BOX 412 HUNTSVILLE, ALABAMA 35804	

Figure C-3: Recommended Radiometer Instrumentation for WES May '93 Propellant Burn Tests

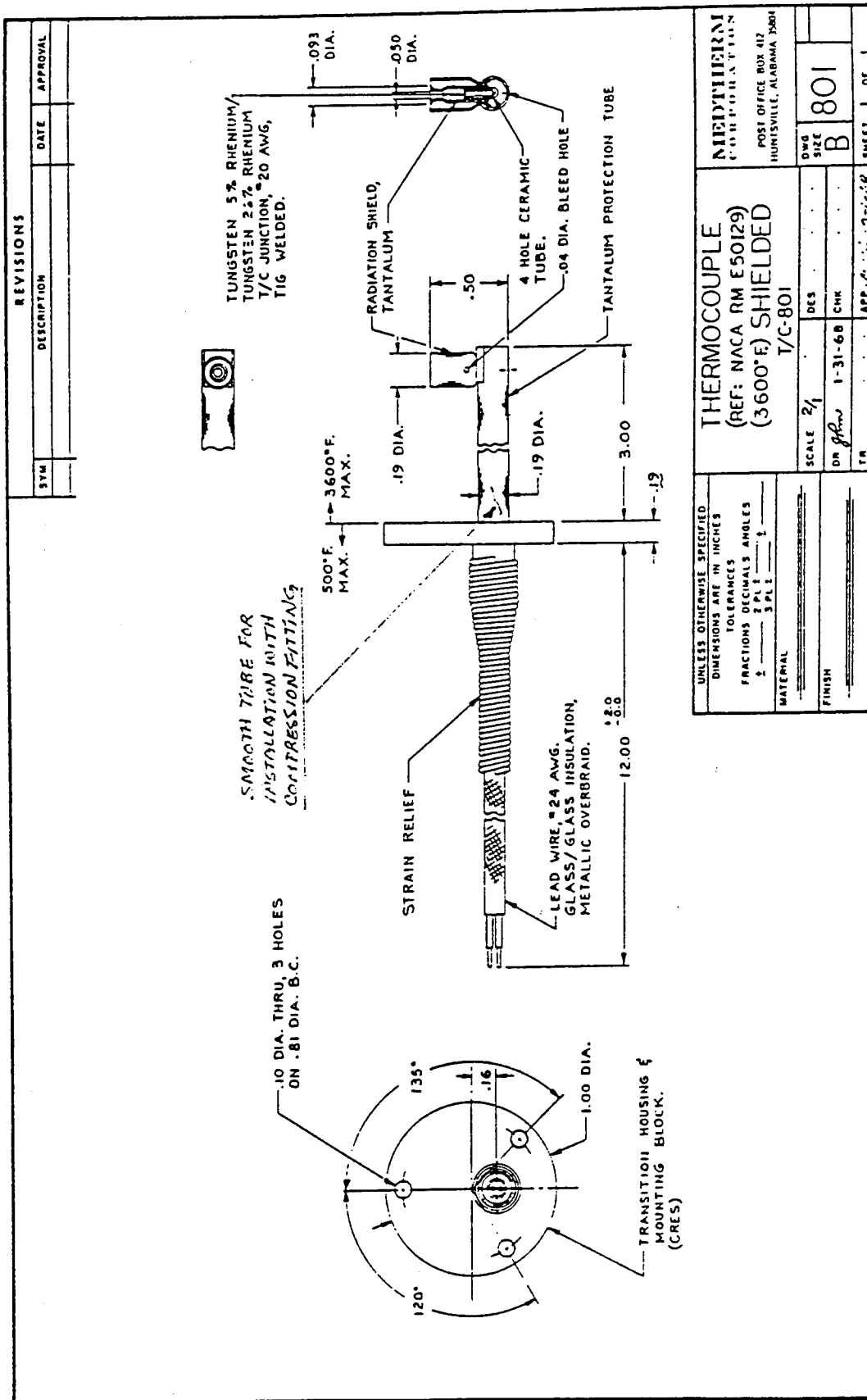


Figure C-4: Recommended Vent Pipe and Plume Total Temperature Instrumentation
for WES May '93 Propellant Burn Tests

DISTRIBUTION LIST
US/ROK Technical Organizations

<u>No. of Copies</u>	<u>No. of Copies</u>
<p>Commander Office of the Assistant Secretary of the Army (Research, Development & Acquisition) ATTN: SARD-IN RM 3E416 Washington, DC 20310-0103</p>	<p>Chairman Department of Defense Explosives Safety Board ATTN: Technical Library Hoffman Building 1 2461 Eisenhower Avenue Alexandria, VA 22331</p>
1	1
<p>Ministry of National Defense Logistics Bureau ATTN: Colonel Yeon Woo Chung 1 Yongsan 3ka-dong Yongsan-ku Seoul KOREA 120-023</p>	<p>Applied Research Associates, Inc. ATTN: Mr. Charles Needham Suite A220 4300 San Mateo Blvd., NE Albuquerque, NM 87110</p>
1	1
<p>Director U.S. Army Defense Ammunition Center and School ATTN: SMCAC-PMUAST (Mr. Gary Abrisz) Savanna, IL 61074-9639</p>	<p>Agency For Defense Development ATTN: Dr. Song, So-Young ADD 1-3-7 P.O. Box 35 Dae-Jeon, 300-600 REPUBLIC OF KOREA</p>
5	3
<p>Chairman Department of Defense Explosives Safety Board ATTN: DDESB-KT (Dr. Chester Canada) 2461 Eisenhower Avenue Alexandria, VA 22331-0600</p>	<p>Director Defense Nuclear Agency ATTN: TDTR (Mr. Tom Kennedy) SPWE (Dr. Ed Tremba) SPSD (Dr. K. Goering) 6801 Telegraph Road Alexandria, VA 22310-3398</p>
1	1 1 1
<p>Commander U.S. Army Corps of Engineers Omaha District ATTN: CEMRO-ED-SH (Mr. William Gaube) 215 North 17th Street Omaha, NE 68102-4978</p>	<p>Air Force Armaments Laboratory ATTN: ASD/YQI (Mr. J. Jenus) Eglin AFB, FL 32542-5434</p>
1	1
<p>Naval Weapons Center Conventional Weapons Division Ordnance Evaluation Department ATTN: Mr. Carl C. Halsey (Code 3269) China Lake, CA 93555-6001</p>	<p>Commander Defense Nuclear Agency ATTN: FCTT (Dr. Byron Ristvit) FCTT (Dr. Eric J. Rinehart) 1680 Texas St., SE Kirtland AFB, NM 87117-5669</p>
1	1 1
	<p>Commander Air Warfare Center ATTN: Code 326B (Mr. L. Josephson) China Lake, CA 93555-6001</p>
	1

	<u>No. of Copies</u>		<u>No. of Copies</u>
Commanding Officer Naval Ordnance Station ATTN: Technical Library Indian Head, MD 20640	1	Headquarters, U.S. Air Force ATTN: SEP (Mr. Paul Price) 1400 Air Force Pentagon Washington, DC 20330-1400	1
Commander Belvoir Research, Development and Engineering Center ATTN: AMXME-ND Fort Belvoir, VA 22060	1	Director U.S. Army Research Laboratory ATTN: AMSRL-WT-TB (Mr. John Starkenberg) Aberdeen PG, MD 21005-5066	1
Chief of Engineers Department of the Army ATTN: CERD-ZA 20 Massachusetts Ave. Washington, DC 20314	1	Commander Naval Surface Warfare Center Dahlgren Division ATTN: Code R10H (Mr. Michael Swisdak) 10901 New Hampshire Avenue Silver Spring, MD 20903-5000	1
Southwest Research Institute ATTN: Mr. K. Marchand 8500 Culebra Road San Antonio, TX 78206	1	Commander Naval Facilities Engineering Service Center ATTN: Code ESC-62 (Mr. James Tancreto) Port Hueneme, CA 93043-5003	1
Applied Research Associates ATTN: Mr. J. L. Drake 3202 Wisconsin Ave. Vicksburg, MS 39180	1	Commander Air Force Weapons Laboratory ATTN: NTEDE (Dr. Henny) Kirtland AFB, NM 87117-6008	1
PM AMMOLOG ATTN: AMCPM-AL (Mr. Bob Rossi) Picatinny Arsenal, NJ 07806-5000	1	Director Harry Diamond Laboratories ATTN: SLCHD-NW-RA 2800 Powder Mill Road Adelphi, MD 20783-1197	1
Bakhtar Associates ATTN: Dr. K. Bakhtar 2429 West Coast Highway, Suite 201 Newport Beach, CA 92663	1		
Commander U.S. Army Research Laboratory ATTN: SLCBR-TB-EE (Dr. R. Frey) (Mr. O. Lynn) Aberdeen Proving Ground, MD 21005	1 1		
U.S. Army Corps of Engineers Huntsville Division ATTN: CEHND-ED-CS (Mr. Paul Lahoud) P. O. Box 1600 Huntsville, AL 35807-4301	1		

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE May 1996	3. REPORT TYPE AND DATES COVERED Final report	
4. TITLE AND SUBTITLE Improved Techniques for Measuring Thermal Effects of Propellant Burn Tests in Confined Areas			5. FUNDING NUMBERS Contract No. DACA39-92-M-7281	
6. AUTHOR(S) E. C. Knox				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) REMTECH, Incorporated 2905 West Corp Boulevard, Suite 112 Huntsville, AL 35805			8. PERFORMING ORGANIZATION REPORT NUMBER RTR 256-01 UAST-CR-93-004	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army Corps of Engineers Washington, DC 20314-1000 U.S. Army Engineer Waterways Experiment Station 3909 Halls Ferry Road, Vicksburg, MS 39180-6199			10. SPONSORING/MONITORING AGENCY REPORT NUMBER Contract Report SL-96-2	
11. SUPPLEMENTARY NOTES Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) During 1989, WES conducted a series of propellant burn experiments in a partially confined space to evaluate the potential for transition from deflagration to detonation. Pressure, temperature, and thermal flux-time histories were recorded. These data were analyzed in terms of quality and interchannel compatibility to develop improved instrumentation/techniques for measuring the thermal effects of propellant deflagration. In addition, a one-dimensional model was developed characterizing the propellant thermochemical properties and flow processes. This report documents the data analyses, thermal model development, comparison of model and measured data, and recommendations for improved thermal instrumentation.				
14. SUBJECT TERMS Deflagration M-1 propellant Propellant burn			15. NUMBER OF PAGES 54	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LITIGATION OF ABSTRACT	